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Research Article

Dynamics of Spatio-Temporal Trend and Predictability of Malaria Across India (1995–2025)

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A B S T R A C T

This study examined spatio-temporal trends and geographical distribution across Indian states on a year-by-year basis (1995-2025) to assess the cases of malaria using log-linear regression (R^2) values, Modified Mann-Kendall (MMK) Z-Score Test and Sen's slope estimates as well as maps of cumulative burden for each state. Nationally, there has been a statistically significant and monotonic decrease in malaria cases over time, with considerable support from both MMK Z-Score results as well as Sen's slope estimates. Multiple states in central, eastern, and southern India with historical endemicity for malaria had high R^2 values, indicating that they have had stable and predictable decreases in malaria cases over time. While major northeastern states such as Arunachal Pradesh, Assam, and Manipur exhibit high R^2 values and significant declining trends, other specific pockets within the northeastern region (such as Meghalaya, Mizoram, and Tripura), along with Sikkim and the island regions, display low R^2 values and also non-significant MMK trends in some states, indicating that these localized areas continue to experience irregular, outbreak-driven transmission. The spatial clustering of malaria cases reveals a portion of the country that was once referred to as the Malaria Belt - Odisha, Chhattisgarh, Madhya Pradesh, and the adjoining states - but has now shown a dramatic decline in the cases of malaria while retaining a history of having had a high cumulative burden of malaria in the past. The findings of this study demonstrate that there are multi-speed geographical transitions occurring across the country with respect to malaria. Therefore, while the national goal of malaria elimination is achievable, regionally specific vulnerabilities will remain and will require targeted, contextually relevant interventions.

Keywords: Malaria, Trends and Patterns, Sen Slope, Log-Linear Regression

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Introduction

Malaria is a life-threatening disease transmitted by the bite of an infected female Anopheles mosquito.[1] After the ingestion of the parasite into the human bloodstream, the Plasmodium parasite infects the liver and red blood cells, as a result of which the patient develops symptoms of the disease, including fever, chills, sweating, headache, weakness, vomiting, joint pains, and anaemia.[2] In the event of the disease remaining untreated, the disease progresses to life-threatening complications, which include jaundice, seizures, renal and multi-organ failure, coma, and death, and the most at-risk groups include children under the age of five and pregnant women.[3,4] The same pathological conditions and vulnerabilities exist in India, where the disease is prevalent in areas where there is no proper access to diagnosis and treatment.[5] Of the four human Plasmodium species, Plasmodium (P.) falciparum and Plasmodium vivax contribute to the large number of cases of malaria worldwide, as well as in the Indian subcontinent.[6] P. falciparum is known to be responsible for severe as well as fatal cases of malaria, while P. Vivax is a threat because of its ability to enter a dormant state in the liver, leading to reinfections, even after the administration of treatment.[7] Climate-related, socio-environmental factors such as high temperatures, humidity, rainfall, inadequate housing, as well as poverty, which are common in a few Indian states, in particular those that are forested, contribute to the extent of the Indian malaria situation.[8–10]

Globally, an estimated 2.3 billion cases and 14 million deaths have been averted by sustained efforts in malaria control since 2000.[11] Malaria still retains its significance as one of the major public health issues in the world.[12] It has been observed that the World Health Organisation African Region again retains the highest number of cases and deaths due to malaria.[13,14] The global problems related to malaria control, which affect India immediately, include resistance to medication, resistance to insecticides, climate change, and financial deficits.[15]

India has been a key player in the global fight against malaria and has made impressive strides in the last 30 years, reducing the number of cases from approximately 2 million and the number of deaths from more than 20, 000 in the 1990s to less than 200, 000 cases and around 100 deaths between 2021 and 2024.[16] Such a decline in cases can be largely credited to the implementation of consistent measures provided by the national programmes like NVBDCP and NCVBDC that focused on improving surveillance, vector control, rapid diagnostics, and case management.[17] Nevertheless, malaria transmission is still a challenge in India, which is a vast country with major geographical differences and complex epidemiological patterns.[18] A significant burden of the disease, i.e., about 80-90% of the reported cases, falls on Odisha, Chhattisgarh, and Jharkhand, where the infection is predominantly caused by Plasmodium falciparum in the tribal and forest-dwelling populations.[19,20] Besides that, some areas in Northeast India have also experienced continuous transmission due to the effects of a combination of the difficult terrain, the forest ecosystem, cross-border movement, and poor healthcare facilities.[21,22]

Over the last few years, emerging hotspots in West Bengal and Maharashtra reflect changing transmission dynamics associated with population migration, urban expansion, environmental modification, and climatic variability since 2020.[21,23] Although national cases fell dramatically from 1.6 million in 2010 to 186,532 in 2020 and remained low post-COVID, the proportion of P. falciparum infections increased to nearly 60% by 2023, associated with drug resistance and marked inter-state variability.[5,24,25] India has strengthened its efforts for elimination through the National Strategic Plan for Malaria Elimination 2023–2027, targeting the elimination of indigenous transmission by 2027-a target aligned with the global goal of a 90% reduction by 2030-emphasizing the need for sustained and region-specific interventions together with climate-sensitive ones to avert resurgence.[26]

This paper is a comprehensive examination of trends and the spatial distribution of malaria in India from 1995 to 2025 using state-level surveillance statistics. This paper employs log-linear regression analysis, Modified Mann-Kendall trend test analysis, and Sen's slope estimate analysis to study temporal trend changes and spatial analysis to map distribution variability regarding the magnitude of the malaria load. Through the integration of statistical trend analysis and spatial analysis, this research work is a complete system for studying epidemiology in planning the strategic elimination of malaria and intervention measures for controlling malarial cases in India.

Study area

India, a South Asian country, has a broad range of climates and ecological conditions, from tropical and subtropical plains to mountainous and deltaic regions, shaped by monsoonal rainfall patterns, high forest cover, and variable land-use practices.[27] The ecological heterogeneity translates to high variability in geographical and spatial patterns of malaria distribution and continues to be confined to ecologically suitable and vulnerable regions of forests, tribal, and rural areas of India.[19]

Geographically, India is situated between 8°4′–37°6′ N and 68°7′–97°25′ E, approximately covering 3.29 million km (Fig. 1). It is the 7th largest country in the world by area and the most populous, having a population of more than 1.46 billion people with an average density of ~492

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persons/km as of 2025. India is made up of 28 states and 8 Union Territories, with a substantial difference in the level of urbanisation and the availability of health services in different regions. India, in terms of climate, also varies from tropical and dry areas to humid subtropical plains and snow-covered Himalayan regions.

The diverse climate, the monsoon-driven rainfall, the forested landscape, the complicated terrain, and the socio-economic vulnerabilities combine to create ecologically favourable conditions for malaria transmission in India.[28] However, despite substantial reductions in prevalence over recent decades, the disease persists due to ecological suitability, population mobility, urbanisation, and environmental change.[29] In this case, as transmission shifts from widespread occurrence to localised and seasonal patterns, malaria in India remains a context-specific public health challenge that calls for targeted and adaptive control strategies.[30]

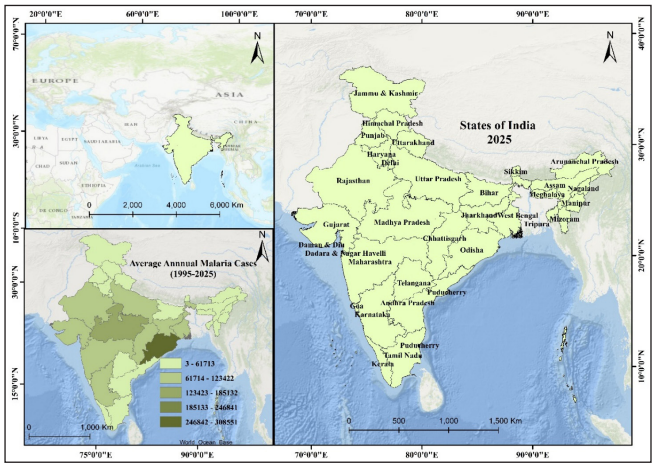


Figure 1.Physical setting of study area

Dataset and Methodology

The annual data for this research have been obtained from the Integrated Disease Surveillance Programme (IDSP), the National Centre for Vector-Borne Diseases Control (NCVBDC), and starred and unstarred questions asked in the Lok Sabha and the Ministry of Health and Family Welfare from 1995 to 2025. Due care of the data is taken for the years for which data is not available, and by default, zero is not considered. It was analysed using RStudio, Microsoft Excel 2024, and ArcGIS. The analysis for Jammu Kashmir and Ladakh is done collectively as it was a single unit till 2019, and separate analysis for 6 year will not yield any useful insight.

To evaluate overall programmatic impact and long-term surveillance trajectories, absolute annual malaria case counts were utilized rather than incidence rates. This approach captures the total operational caseload managed by public health systems across different states and union territories over the three-decade study period. While population-standardized incidence rates are valuable for comparing disease risk across regions of varying population sizes, absolute case counts provide a direct measure of absolute disease burden and resource allocation requirements.

Log-Linear Regression

To evaluate the temporal trajectories of malaria cases across states from 1995 to 2025 while accounting for the non-negative and skewed nature of epidemiological count data, log-transformed linear regression models were fitted. Case counts (y) were transformed using $\log(y+1)$ to accommodate zero-value observations safely. Model predictions and associated 95% confidence intervals were subsequently back-transformed to the original scale using the exponential function minus one ($\exp(\text{“fit”})-1$). This log-linear framework structurally constrained fitted trends and confidence bounds above zero, eliminating physical impossibilities such as negative case projections while maintaining clarity in evaluating long-term directional trends and coefficients of determination (R^2).[20,31,32]

$$\ln(y+1) = \beta_0 + \beta_1 x AZ\varepsilon \quad (1)$$

where *y* represents the total number of malaria cases (dependent variable), *x* denotes time in years (independent variable), is the regression slope indicating the average annual change in cases, is the intercept, and is the error term capturing unexplained variation.

Coefficient of Determination

The Coefficient of Determination (R^2) quantifies temporal and spatial heterogeneity in malaria trends by measuring the proportion of variation in reported cases explained by time. Higher R^2 values indicate stable and predictable transmission, while lower values reflect irregular, outbreak-driven dynamics.[20,33,34]

$$R^2 = \frac{SSR}{SST} \quad (2)$$

$$SSR = \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2 \quad (3)$$

$$SST = \sum_{i=1}^{n}(y_i - \bar{y})^2 \quad (4)$$

Where SSR (Sum of Squared Regression): $\Sigma\ (\hat{y}_i - \bar{y})^2$, representing the variation explained by the regression model; SST (Total Sum of Squares): $\Sigma\ (y_i - \bar{y})^2$, representing total variation in malaria cases; y_i: Observed malaria cases, $\hat{y}_i$: Predicted malaria cases, and $\bar{y}$: Mean of observed malaria cases.

Modified Mann-Kendall Test

The Modified Mann–Kendall Test (MMKT) detects monotonic trends similar to the conventional Mann–Kendall test but incorporates a variance correction to account for

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serial autocorrelation in time-series data.[35]This adjustment enhances the robustness of trend significance estimates when observations are temporally dependent.[35–37] In this study, MMKT is employed to evaluate the statistical significance of long-term trends in malaria cases across Indian states during 1995–2025. The test is based on the Mann–Kendall statistic *S*, computed from all pairwise differences between later and earlier observations in the time series ($x_j - x_i$, where $j > i$). Positive and negative values of *S* indicate increasing and decreasing trends, respectively.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(xj - xi) \quad (5)$$

The standardized test statistic (*Z*) is computed from the Mann–Kendall statistic (*S*) and its variance, assuming a standard normal distribution. The *Z*-value indicates the presence and direction of a monotonic trend, with positive and negative values representing increasing and decreasing trends, respectively, while values near zero indicate the absence of a significant trend.

$$\mathrm{Var}(S) = \frac{1}{18}[n(n-1)(2n+5) - \sum_t f_t(f_t-1)(2f_t+5)] \quad (6)$$

Here Var(S) is unadjusted variance of calculated from the original time series, ft is the extent/frequency of ties in the data group and n is total number of observations

$$Z = \begin{cases} (s-1)/\sqrt{VS}, & s > 0 \\ 0, & s = 0 \\ (s+1)/\sqrt{VS}, & s < 0 \end{cases} \quad (7)$$

In this study, we apply the method of Hamed and Rao, with the correction factor suggested by Hamed & Ramachandra Rao 1998 & Rao et al., 2003.

$$V(S) = cf * v(S) \quad (8)$$

$$Cf = 1 + \frac{2}{N(N-1)(N-2)} \sum_{k=1}^{N-1} (N-k)(N-k-1)(N-K-2) r_k^R \quad (9)$$

In this context, v(*S*) represents the variance of S (or var) calculated from the original time series of Mann-Kendall's test, r_k^R computed autocorrelation coefficient of the rank-transformed series; V(*S*) is the variance of S calculated after the correction, and Cf is the correction factor suggested by Hamed & Ramachandra Rao (1998).

Sen's Slope test

Sen's slope is a non-parametric estimator used to quantify the magnitude of a monotonic trend in time-series data[38]. In this study, it estimates the annual rate of change in malaria cases across India during 1995–2025. Its application is suitable for malaria cases data, which are often irregular, non-normal, and influenced by variability and outliers, as Sen's slope provides a robust, distribution-free measure based on the median of pairwise slopes.[36,39,40]

$$\text{Sen's Slope} = \mathrm{Med}\left\{\frac{x_j - x_i}{j-i} : i < j\right\} \quad (10)$$

The vector i < j contains a pair of items, where i represents the earlier year and j the later year. Equation (10) yields the following estimates of Sen's slope value for each year:

$$\left\{\frac{x_j - x_i}{j-i} : i < j\right\} \quad (11)$$

Result and Discussion

Trends

The state-wise log-linear regression trends (Fig. 2) in malaria cases across India over the last three decades, with particular emphasis on the coefficient of determination (R^2) as an indicator of the strength, stability, and predictability of temporal change, show robust decreasing trends. The R^2 values vary markedly across states, reflecting substantial geographical heterogeneity in how consistently malaria cases have evolved.

States with relatively high R^2 values (≥0.60) include Arunachal Pradesh (0.909), Tamil Nadu (0.852), Chhattisgarh (0.830), Assam (0.795), Uttar Pradesh (0.766), Karnataka (0.761), Andhra Pradesh (0.713), Odisha (0.683), Madhya Pradesh (0.670), Manipur (0.639), Uttarakhand (0.659), Goa (0.605), Rajasthan (0.603), and Kerala (0.603).These states have exhibited a stable and consistent level of reduction in malaria incidents year to year as opposed to having had high levels of variability from year to year. This indicates that malaria has been effectively reduced through continued intervention and improved systems of disease control.[41,42] Further, many of these states were located within the historical regions of malaria transmission, indicating that there is a strong correlation between historic programmatic attention to malaria control in these states and the relative stability of long-term epidemiology outcome.[43]

States at a moderate level on the R^2 scale (ranging between 0.30 and 0.60) such as Gujarat (0.599), West Bengal (0.588), Telangana (0.582), Jharkhand (0.557), Maharashtra (0.530), Puducherry (0.486), Nagaland (0.459), Delhi (0.457), Dadra & Nagar Haveli and Daman & Diu (0.441), Jammu & Kashmir (0.418), Bihar (0.399), Himachal Pradesh (0.327), Punjab (0.309), and Chandigarh (0.302) exhibit moderate consistency for malaria trends. Evidence of total decline with sporadic peaks produces an inconsistent representation of declining malaria cases in most of these states. The majority of these states are examples of "transitional epidemiology", where the mix of urbanization, population movement, development of irrigation, and heterogeneous vector ecologies creates a unique environment for the transmission of malaria[44]. The moderate values of R^2 therefore do not represent a sufficient explanation for understanding the timing or functional relationship of the linear trends to malaria in these areas.

Conversely, those states and Union Territories with a low R^2 (R^2<0.30) include Haryana (0.297), Sikkim (0.222), Andaman & Nicobar Islands (0.130), Meghalaya (0.115), Tripura (0.008), Mizoram (0.003), and Lakshadweep (0.002) exhibit weak to absent relationships with malaria cases and

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time, suggesting that there are minimal or insignificant linear relationships between time and malaria cases, or no trends present at all. Most of these regions have significant variability in their annual malaria cases; are subject to cyclical malaria outbreaks, or have persistently low case rates[45–47]. The geographical positions of most of the states are islands, mountainous regions, forest-covered areas, and on the northeastern fringe of India where local environmental and socio-ecological circumstances significantly influence the transmission of malaria rather than gradual changes over time[46,48].

Modified Mann-Kendall Test (Hamed & Rao), the Sen slope estimator and their spatial representation of the Modified Mann-Kendall Test consistently show and support each other on the long-term trend of decreased malaria in India from 1995 to 2025(Table 1 & Fig 3). The MMK statistics provide statistical evidence for the significant and monotonic nature of the trend.

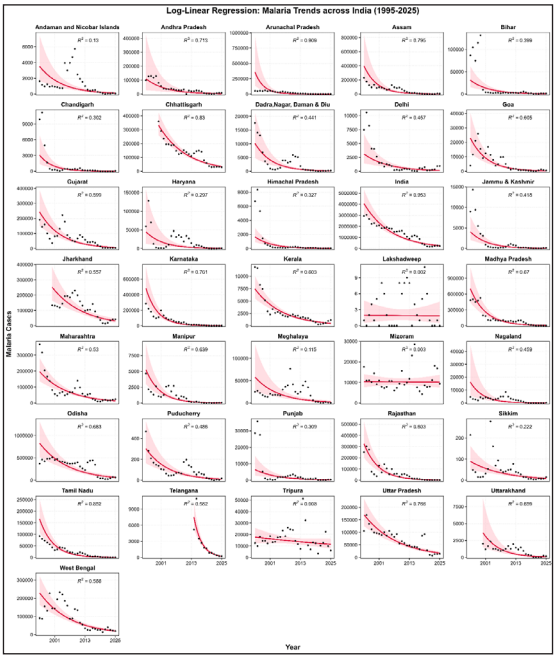


Figure 2.State wise trend analysis of malaria cases in India from 1995 to 2025

Table 1.Statistical significance of Malaria trends in India (1995-2025)

Spatial_ Unit	Z_ value	p_ value	Tau	Sen_ Slope	Interpretation
Andaman & Nicobar	-2.385	0.01707	-0.527	-44.211	Statistically significant Decreasing trend
Andhra Pradesh	-3.503	0.00046	-0.781	-2541.333	Statistically significant Decreasing trend
Arunachal Pradesh	-4.513	<0.00001	-0.88	-2177.154	Statistically significant Decreasing trend
Assam	-5.011	<0.00001	-0.794	-5006.867	Statistically significant Decreasing trend
Bihar	-2.555	0.01	-0.583	-188.947	Statistically significant Decreasing trend
Chandigarh	-4.583	<0.00001	-0.683	-23.75	Statistically significant Decreasing trend
Chhattisgarh	-4.284	0.00002	-0.778	-9105.182	Statistically significant Decreasing trend
Dadra, Nagar, Daman &Diu	-4.546	<0.00001	-0.604	-184.062	Statistically significant Decreasing trend
Delhi	-2.274	0.02298	-0.499	-92.25	Statistically significant Decreasing trend
Goa	-4.235	0.00002	-0.712	-480.5	Statistically significant Decreasing trend
Gujarat	-11.929	<0.00001	-0.716	-4827.724	Statistically significant Decreasing trend
Haryana	-3.672	0.00024	-0.471	-1386	Statistically significant Decreasing trend
Himachal Pradesh	-3.159	0.00159	-0.719	-15.75	Statistically significant Decreasing trend
India	-6.795	<0.00001	-0.867	-89391.667	Statistically significant Decreasing trend
Jammu & Kashmir	-3.847	0.00012	-0.676	-52	Statistically significant Decreasing trend

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Jharkhand	-2.044	0.04098	-0.514	-6138.3	Statistically significant Decreasing trend
Karnataka	-4.876	<0.00001	-0.931	-5649.55	Statistically significant Decreasing trend
Kerala	-4.548	<0.00001	-0.837	-142	Statistically significant Decreasing trend
Lakshadweep	0	1	0	0	No statistically significant trend
Madhya Pradesh	-3.87	0.00011	-0.845	-8110.75	Statistically significant Decreasing trend
Maharashtra	-4.132	0.00004	-0.617	-4136.222	Statistically significant Decreasing trend
Manipur	-4.1	0.00004	-0.699	-75.071	Statistically significant Decreasing trend
Meghalaya	-1.353	0.17591	-0.29	-754.429	No statistically significant trend
Mizoram	-0.477	0.63326	-0.062	-35	No statistically significant trend
Nagaland	-2.947	0.0032	-0.568	-160.923	Statistically significant Decreasing trend
Odisha	-3.254	0.00114	-0.604	-14697	Statistically significant Decreasing trend
Puducherry	-3.711	0.00021	-0.598	-6	Statistically significant Decreasing trend
Punjab	-2.822	0.00477	-0.439	-113.25	Statistically significant Decreasing trend
Rajasthan	-6.153	<0.00001	-0.781	-4301.833	Statistically significant Decreasing trend
Sikkim	-2.157	0.03101	-0.473	-2.143	Statistically significant Decreasing trend
Tamil Nadu	-4.835	<0.00001	-0.927	-2264.6	Statistically significant Decreasing trend
Telangana	-2.943	0.00325	-0.939	-430.107	Statistically significant Decreasing trend
Tripura	-0.99	0.32199	-0.155	-123.5	No statistically significant trend
Uttar Pradesh	-5.983	<0.00001	-0.759	-3801.529	Statistically significant Decreasing trend
Uttarakhand	-3.054	0.00226	-0.551	-69.364	Statistically significant Decreasing trend
West Bengal	-3.877	0.00011	-0.622	-5648.9	Statistically significant Decreasing trend

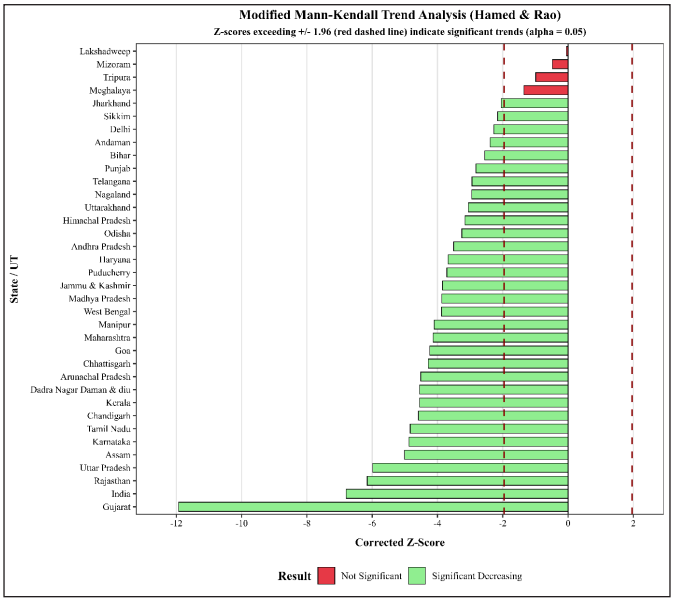


Figure 3.Visual representation of the Modified Mann-Kendall Test (MMKT)

National and Core-Region Decline

On a nationwide basis, there is a significant, strongly negative MMK Z-value with a very substantial, large negative Sen's slope, indicating absolute and measurable evidence of a major, and continuing decline in malaria cases throughout all of India. The alignment of the statistically significant MMK results with the magnitude of the slope proves that the national decline is statistically solid and is epidemiologically relevant in absolute terms, as opposed to statistical terms.

The States that have the Most Negative Sen's Slope Values are States where historically there have been very high

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burdens of malaria and malaria transmission: Odisha, Chhattisgarh, Madhya Pradesh, Maharashtra, Karnataka, Andhra Pradesh, West Bengal, Gujarat, Rajasthan, Uttar Pradesh, and Assam. These States, also have demonstrated negative, statistically significant MMK Z-Scores, suggesting that in These States the malaria decline has been sustained, monotonic, and has been entrenched in space for a long time. In other words, for all of these States, they are the product of long-standing control efforts and are a reflection of long-term success in reducing malaria from these areas, as the controlling mechanisms were originally designed to address malaria in these historically forested, tribal, and rural Areas that were the primary core for malaria in India.[43,49]

Magnitude versus Direction: Spatial Differentiation

By using the MMK and Sen's Slope together, it is possible to see both the trend direction and trend magnitude. In the case of several states (e.g. Gujarat, Odisha, Chhattisgarh, Madhya Pradesh, Uttar Pradesh), the large negative Sen's Slope values correspond to very negative Z-Scores. These findings indicate that malaria cases are declining rapidly and consistently in these areas, which are considered areas of highly accelerated epidemiological transition due to their sustained and successful efforts to control malaria.

On the other hand, six states (Bihar, Punjab, Haryana, Delhi, Jammu & Kashmir, Himachal Pradesh, Puducherry) have statistically significant results from the MMK test, but smaller Sen's Slope values than in the states described above. The pattern indicates that while the trend in malaria cases is consistently downward in these states, it appears to be less dramatic than in the high-endemic states. This is likely due to lower levels of cases at the beginning of the analysis period (i.e. low baseline cases), as well as the urban/peri-urban malaria transmission dynamics and greater variability in the number of cases from year to year. All of these states are geographically located in transitional regions where malaria is declining but at a slower rate than observed in former high-endemic areas.

Peripheral and Ecologically Sensitive Regions

The geographical insight is best represented for island territories, northeastern states, and high-altitude areas (or Himalayan regions). The data for Lakshadweep, Meghalaya, Mizoram, & Tripura, illustrate that they have little if any MMK Z-scores and little or no Sen's slopes (both the table and the slope plot). This lack of correlation demonstrates no long-term, monotonic trend rather than conflicting statistics. Geographically, they all have small populations, rugged/complex terrain, and are forested or wooded areas, having trans-boundary flows, and are susceptible to Climate Conditions.[48]

Some of the northeastern and Himalayan states (like Sikkim, Nagaland & Uttarakhand) show large MMK values but only moderate Negative slopes of Sen's, were slow or very small declines but consistent in one direction. These locations demonstrate that malaria elimination is under way; nevertheless, it is unsure and vulnerable to resurgence, mainly due to socio-economic changes or environmental disruption.

Patterns

Regional Clustering of Malaria Trend Predictability across India (1995–2025)

Figure 4 shifts the analytical focus from individual states to spatial clustering and regional coherence in malaria trend predictability, based on R^2 classifications. The map reveals distinct geographical clusters that has underscore India's multi-regional malaria transition.

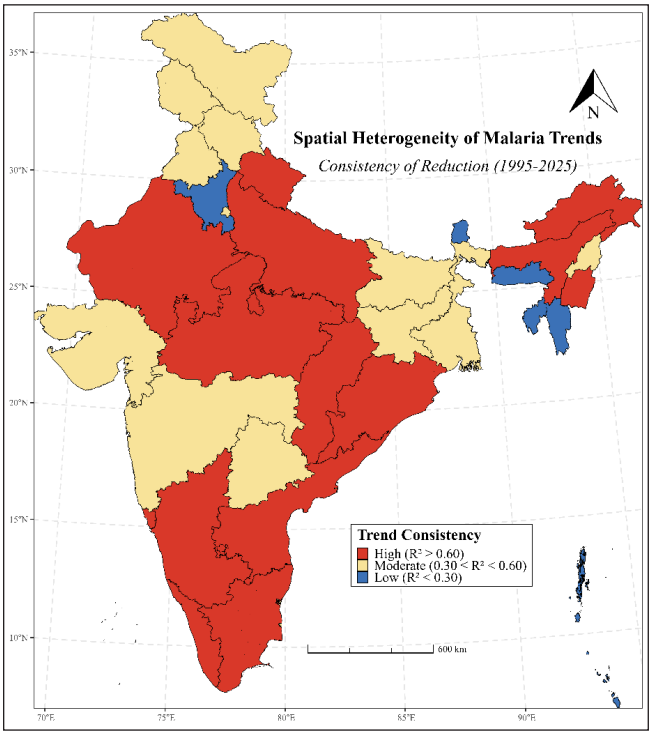


Figure 4.Spatial Heterogeneity of trends of Malaria in India (1995–2025)

A high-predictability cluster ($R^2 \geq 0.60$) exists across central, eastern, southern, and selected northeastern regions of India. This cluster encompasses states such as Odisha, Chhattisgarh, Madhya Pradesh, Karnataka, Andhra Pradesh, Tamil Nadu, Kerala, Rajasthan, Uttar Pradesh, Uttarakhand, Goa, Assam, Arunachal Pradesh, and Manipur. The contiguous nature of this high-predictability cluster indicates that the decrease in malaria cases has occurred in a spatially and temporally coherent manner, suggesting a long-term convergence of disease dynamics across these regions

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The moderate-predictability cluster ($0.30 \leq R^2 < 0.60$) is primarily located on the perimeter of the high-predictability cluster, including northwestern states (Jammu & Kashmir, Punjab, Himachal Pradesh), parts of the Indo-Gangetic Plain (Bihar), central-western corridors (Gujarat, Maharashtra, Telangana, Jharkhand), and selected coastal/northeastern states (West Bengal, Nagaland). Areas within the moderate-predictability cluster represent places of epidemiological transition, characterised by declining trends of malaria transmission during a time of growth from structural uncertainty associated with migration corridors, peri-urban development, varying climatic conditions, and differing programmatic coverage across states[50,51].

The low-predictability cluster ($R^2 < 0.30$) is concentrated in specific ecologically sensitive areas, including the Himalayan state of Sikkim, northwestern lowlands (Haryana), northeastern states (Meghalaya, Mizoram, Tripura), and island territories (Andaman & Nicobar Islands, and Lakshadweep off the southwestern coast). Areas with low R^2 values are subject to significant environmental or climatic changes; therefore, the apparent geographic clustering of these areas indicates continued mean "uncertainty" in the malaria transmission dynamics within these specific regions[52].

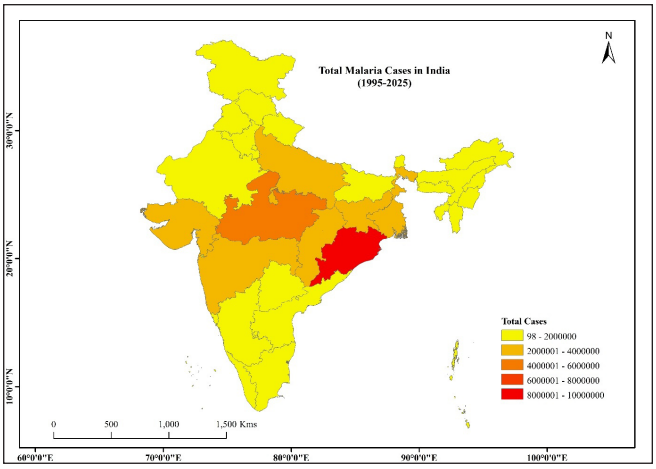


Figure 5.Spatial Distribution of Cumulative Malaria Burden in India (1995–2025)

The map depicts the state-wise cumulative malaria burden in India over the period 1995–2025, revealing a pronounced spatial concentration of malaria cases rather than a uniform national distribution (Fig. 5). A clear geographical gradient is evident, with malaria burden heavily skewed toward central, eastern, and parts of western India, while much of northern, southern, and northeastern India records comparatively lower cumulative case totals.

High-Burden Core Regions

Eastern and Central India have the highest cumulative burden of malaria[53]. Of these areas, the State of Odisha, which falls under the highest recorded class (8,000,001-10,000,000), has emerged as the area showing the greatest concentration. The numbers recorded for Odisha show the longstanding ecological propensity of the state toward transmitting malaria as a result of dense forested areas, tribal heavy districts, humid tropical weather conditions, and limited access to medical and public health institutions (Mishra et al., 2023). Hence, the records demonstrate that Odisha has acted as a prominent malaria epicentre for the past 30 years despite recent declines of malaria in Odisha (Mishra et al., 2023).

Intermediate Burden Zones

Surrounding the primary epicenter, a broad belt of central and eastern states falls within the moderate cumulative burden tier. This continuous geographic corridor includes Madhya Pradesh, Chhattisgarh, Jharkhand, West Bengal, Maharashtra, Gujarat, and Uttar Pradesh which has moderate to high cumulative burden between 2,000,001 – 8,000,000 cases. Together, these seven states comprise a contiguous area of significant malaria burden through the central, east, and East-Central Region of India.[15] The geographic and socio-ecological characteristics common to the contiguous states continue to perpetuate the spread of malaria through the land interconnected within this belt and have continued thusly through long periods of time[55]. In addition, the cumulative burden across multiple states is indicative of both periodicity in transmission and local endemicity linked with different types of transmission consistent with rivers, irrigated agriculture, expansion of urban boundaries, and movement of people.[15]

Low Burden Areas

The Northern region, Himalayan (N & NE), Southern Peninsular states of India and the Islands represent locations with very little cumulative burden (≤2,000,000 cases) based on the number of cases reported through 2025. There are limited numbers of malaria cases due to intermittent transmission patterns, low intensity of transmission, or abrupt control because of cooler climates and fewer vector populations.[56] A low cumulative burden does not necessarily mean the area is malaria-free; rather, in ecologically sensitive regions, outbreaks may still occur due to environmental instability and may persist for some time.

Geographical Synthesis

Geographically, the spatial concentration of malaria burden in India for the past 30 years is most pronounced among a small number of states in central and eastern regions, which have contributed to nearly half of the cases reported across India over this time period. This pattern of spatial concentration supports the trend analyses, showing that many of these high-burden states are currently experiencing declines that are statistically significant and reflect a

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transition from high transmission to ongoing reduction. Ultimately, the cumulative distribution depicts the spatial nature of India's malaria issue and the relationship between this challenge and the historical ecological and socio-economic context of India. Although the national trends are towards declining malaria case rates, the long-standing high cumulative burden in these regions should drive sustained region-specific elimination efforts, especially in historically endemic core regions.

Limitations

While this study provides a comprehensive spatio-temporal evaluation of malaria trends across India from 1995 to 2025 using complete annual datasets, several limitations should be acknowledged:

- **Surveillance and Reporting Artefacts:** Disease case records are subject to passive surveillance inconsistencies, varying diagnostic capacities, and regional differences in reporting compliance over the study period.
- **Absence of Species Disaggregation:** The analysis evaluates total aggregate case counts without disaggregating trends by specific parasite species (*Plasmodium falciparum* versus *Plasmodium vivax*), which possess distinct transmission dynamics and clinical profiles.
- **Macro-Level Spatial Aggregation:** Utilizing state-level administrative boundaries masks localized micro-environmental variations, localized vector control interventions, and sub-state transmission heterogeneities.

Recommendation and Conclusion

The collective evidence from the log-linear regression (R^2) statistical analysis, Modified Mann-Kendall test statistics, Sen's slope estimates, and spatial map of cumulative burden over time provides strong evidence to support that malaria has significantly decreased through a sustained decline in India from 1995 through to 2025. In general terms nationally, the negative and large magnitude of Z-scores and Sen's slope indicate an overall downward trend for malaria control programs, which shows the success of long-term malaria prevention and control programs. However, there is an uneven decrease in some regions within India. The states of central, eastern, and southern India, historically known to be the core of malaria transmission, have both high cumulative burden levels and well-defined and anticipated decreases, indicating an epidemiological shift associated with the steady increase in treatment and preventative interventions. Northeastern states such as Arunachal Pradesh, Assam, and Manipur have high R^2 values and significant declining trends; other specific states such as Meghalaya, Mizoram, and Tripura, along with Sikkim and the island regions, have low R^2 values and also non-significant MMK trends in some states, indicating that these localized areas continue to experience irregular, outbreak-driven transmission that is possibly impacted by various factors including complicated ecological, geographic, travel, and immigration-related conditions.

The implications from these contrasting geographical locations are that malaria eradication in India is no longer limited to using methods that reduce cases on a national scale but is now relying on geographic vulnerabilities. Future approaches should therefore switch from using the same model across all areas to differentiated, risk targeted models. Enhancing climate and environmental sensitive monitoring systems in low prediction areas, maintaining enhanced prevention efforts in the former high-endemic areas to avoid resurgence, and integrating the effects of climate change and human movement into the process of designing control programs is critical for sustaining continued drops in malaria cases. To eliminate malaria and maintain, that goal in India will require addressing residual spatial heterogeneity with region specific interventions while capitalizing on the gains made in areas that have moved to low endemicity.

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Author contributions

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