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## Climatic Determinants and Spatial Hotspots of Malaria Incidence in Lama Upazila, Bangladesh (2020–2024)

Hasibul Ahmed Pulok<sup>1</sup> and Syed Hafizur Rahman<sup>2\*</sup>

<sup>1</sup>Graduate student, Department of Environmental Sciences, Jahangirnagar University, Savar, Dhaka-1342, Bangladesh.

<sup>2</sup>Proferssor, Department of Environmental Sciences, Jahangirnagar University, Savar, Dhaka-1342, Bangladesh.

### Abstract

Malaria remains a major public health concern in Lama Upazila, a high-burden area within Bangladesh's Bandarban district. This study investigates the relationship between malaria incidence and key climatic variables—temperature, rainfall, and relative humidity—along with their lagged effects across eight unions. A total of 8,713 malaria cases were recorded from 2020 to 2024, with climate data sourced from ERA5-Land (9 km resolution) and malaria incidence data from BRAC's microstratification report. Analytical methods included Spearman's rank correlation, time series analysis, and hotspot detection using Getis-Ord  $G_i^*$ . Rainfall and humidity consistently showed strong positive correlations with malaria incidence. Notably, rainfall had peak correlations of 0.91 in Rupasipara and Gajalia in 2023 and 0.93 in Sarai in 2024. Humidity peaked at 0.97 in Rupasipara (2023) and 0.94 in Sarai (2021). Temperature showed moderate and more variable correlations, reaching 0.79 in Gajalia and 0.75 in Sarai in 2024 but dropping to 0.48 in Lama and -0.02 in Pouroshova in 2023. Lagged effects were most significant at a 1-month lag, with temperature correlating up to 0.78 in Sarai and Fanshiakhali, rainfall up to 0.86 in Pouroshova, and humidity up to 0.88 in Lama. These effects generally declined with longer lags. Time series analysis revealed strong seasonality, with consistent peaks during the monsoon (June–August), especially during a major outbreak in June 2022 (978 cases). The lowest incidence was recorded in April 2020 (8 cases). Hotspot analysis identified Lama and Rupasipara as persistent malaria hotspots from 2020 to 2024, with Rupasipara reaching an Annual Parasite Index (API) of 80.71 in 2022. Other unions exhibited low or irregular transmission without cold spot clustering.

**Keywords:** *Malaria surveillance, Spatial epidemiology, Lagged climatic effects*

### Introduction

Climate change poses one of the most significant global health threats of the 21st century, with its impacts increasingly evident in climate-sensitive regions like Bangladesh. Due to its geographical location, high population density, poverty, and heavy dependence on natural resource-based livelihoods, Bangladesh is particularly vulnerable to climate-induced health risks (CCC, 2009; WHO, 2003). Among these health risks, vector-borne diseases, particularly

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\*Corresponding Author: [hafizsr@juniv.edu](mailto:hafizsr@juniv.edu)

malaria, have shown increasing sensitivity to climatic variability over the past three decades, driven by changes in temperature, rainfall, and humidity (Gubler, 1996; Gubler, 2001).

Malaria remains endemic in specific regions of Bangladesh, notably the Chittagong Hill Tracts (CHT), where ecological and topographical conditions support the survival of *Anopheles* mosquitoes, the primary malaria vector (WHO, 2005). Lama Upazila, a subdistrict of Bandarban within the CHT, exemplifies such an environment, with rugged terrain, forest cover, and low-elevation valleys providing ideal breeding habitats for mosquitoes. Despite national progress in malaria control, which saw an 81% reduction in reported cases between 2010 and 2018, the resurgence of cases since 2019 highlights the fragility of these gains (National Malaria Control Program, 2017). Recent surveillance data reveal a dramatic increase in national malaria cases from 6,130 in 2020 to 16,567 in 2023, with Bandarban district accounting for over 60% of the burden. Fluctuations in malaria incidence in Lama Upazila mirror this broader trend, with significant variability observed from 2014 to 2022. For instance, cases rose from 3,974 in 2015 to 4,127 in 2022, following a temporary decline in 2020 (1,081 cases), reflecting the complex interplay between climatic conditions and disease dynamics ([www.malariaapitracker.com](http://www.malariaapitracker.com)).

Climatic factors influence both the biology of *Anopheles* mosquitoes and the development cycle of *Plasmodium* parasites. Temperature plays a critical role in vector survival, parasite maturation, and transmission potential, with optimal conditions for *P. falciparum* transmission occurring around 24.9°C, bounded by a 12–36°C threshold (Villena *et al.*, 2024). Regional evidence from Mizoram, India—a neighbouring state—indicates higher malaria incidence correlating with peak temperatures between 33.9°C and 35.7°C (Lalmalsawma *et al.*, 2023). Rainfall is also crucial in shaping breeding site availability, with increases during the monsoon season (June–September) associated with malaria peaks in both India and Bangladesh. Monthly rainfall ranging from 86 mm to 284 mm has been linked to transmission surges (Emeto *et al.*, 2020). Additionally, relative humidity influences vector longevity and activity patterns, with studies suggesting that even marginal increases in average annual humidity (e.g., 0.3%) can lead to significant rises in malaria incidence in similar ecological contexts (Reynolds, 2018; Lalmalsawma *et al.*, 2023).

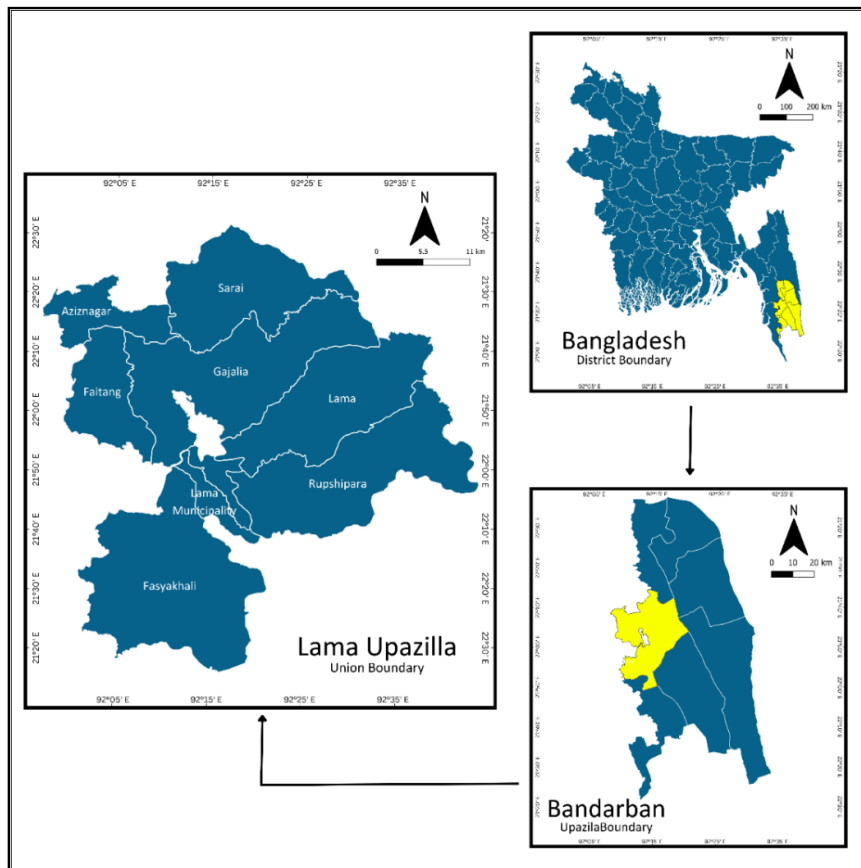
In response to persistent malaria transmission, the Government of Bangladesh launched the National Malaria Elimination Program (NMEP), aiming for complete malaria elimination by 2030. With support from BRAC, the Global Fund, and WHO, the National Strategic Plan (2017–2021) has focused on phased elimination, targeting Cox’s Bazar and the northeast by 2025, followed by the CHT by 2030. Central to this strategy are strengthened surveillance, universal diagnostic access, and climate-adaptive vector control (Noé *et al.*, 2018; National Malaria Control Program, 2017).

Despite these efforts, the localised resurgence of malaria in Lama Upazila underscores the need for granular, climate-informed analyses. Understanding seasonal and lagged associations between climatic variables and malaria incidence is essential for early warning systems, spatial targeting of interventions, and sustaining progress toward elimination. This study seeks to fill this gap by investigating how temporal and spatial variations in temperature, rainfall, and humidity influence malaria trends across unions in Lama Upazila from 2020 to 2024.

## Materials and Methods

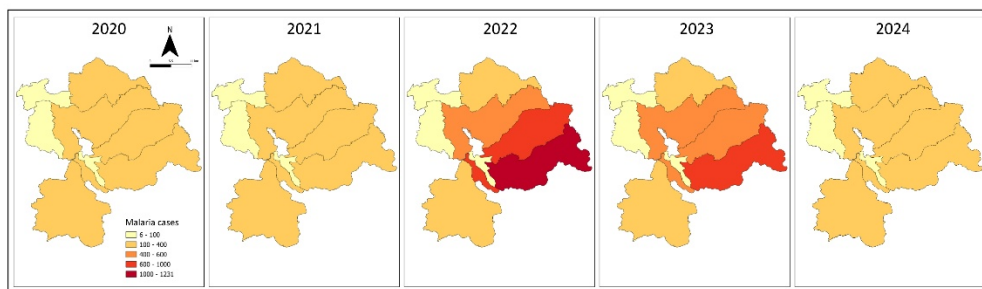
### *Study area*

Lama Upazila, situated within the Bandarban district of Bangladesh's Chittagong Division, presents a geographically and climatically distinct environment, characterised by a tropical monsoon climate with pronounced wet and dry seasons. Lama's environmental conditions directly influence mosquito breeding and malaria transmission dynamics. Recent climatic observations indicate a warming trend, intensified monsoon rainfall, and a slightly extended wet season, suggesting shifts that could impact vector ecology and disease patterns. The spatial boundaries for this study were derived from the Bangladesh Subnational Administrative Boundaries (COD-AB) dataset, which provides shapefiles for administrative levels 0 to 4. This dataset, curated by the Humanitarian Data Exchange and last updated in 2022, was modified to focus specifically on Lama Upazila within the Bandarban district, ensuring precise alignment of climatic and health data with corresponding administrative units.



**Figure 1:** Map of Lama upazila, Bangladesh, depicting union boundaries and the study area.

Lama has experienced fluctuating malaria burdens, with a sharp peak in 2014 followed by a notable decline attributed to enhanced public health interventions. However, a resurgence in 2022 highlights the persistent vulnerability of the area to climatic and programmatic changes. Union-wise malaria distribution further reveals significant intra-upazila variation, with some unions like Rupasipara and Lama Union consistently reporting higher case counts. The study's geographic scope, refined using authoritative subnational administrative boundaries, ensures precise spatial alignment between climatic variables, malaria incidence, and administrative units. These characteristics collectively underscore Lama's relevance as a critical area for investigating the interplay between climate variability and malaria dynamics, providing insights essential for targeted disease control strategies.



**Figure 2:** Union-wise malaria incidence trends in Lama upazila (2020–2024)

(Source: BRAC microstratification reports)

## Methods

### *Climate data collection*

Climatic data were sourced from the ERA5-Land dataset, which is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) under the Copernicus Climate Change Service (C3S) of the European Commission. ERA5-Land offers high-resolution reanalysis data spanning from 1950 to the present, with a spatial resolution of 9 km and hourly temporal granularity. This high-resolution dataset is particularly useful for land surface applications.

Key meteorological variables utilised in this study included 2-meter air temperature, average precipitation, and 2-meter dew point temperature. Relative humidity was calculated using the standard meteorological formula based on air temperature and dew point temperature. Data for the period 1994–2024 were accessed through the Google Earth Engine (GEE) platform. However, for the purposes of this analysis, only the data from 2020 to 2024 were selected to align with the available malaria incidence data.

### *Malaria incidence data collection*

Malaria incidence data for the years 2020 to 2024 were obtained from BRAC microstratification reports. These reports compile data gathered through household surveys and confirmed malaria cases diagnosed via Rapid Diagnostic Tests (RDTs) by BRAC health

### *Climatic Determinants and Spatial Hotspots of Malaria Incidence*

workers. Additional data from local community clinics were also included in BRAC's annual health reports. The malaria case records were aggregated at the union level to maintain spatial compatibility with the climatic and administrative datasets, ensuring consistency in the analysis.

This section outlines the statistical and geospatial approaches used to explore the relationship between climatic factors and malaria incidence across Lama Upazila from 2020 to 2024. A combination of regression analysis, correlation analysis, lagged assessments, time series decomposition, and spatial hotspot detection was applied to reveal temporal patterns, delayed effects, and spatial clustering in malaria transmission dynamics.

**Linear Regression:** This method was used to validate the reliability of recent climatic data by comparing 5-year averages with 30-year historical means. The model's fit was assessed using slope values,  $R^2$ , and p-values, with results visualised in regression plots.

**Spearman's Rank Correlation:** This non-parametric method, supported by t-tests at a 95% confidence level, was applied to quantify non-linear associations between monthly union-level malaria cases and climatic variables such as temperature, precipitation, and relative humidity. The correlation coefficients revealed moderate to strong relationships between these variables.

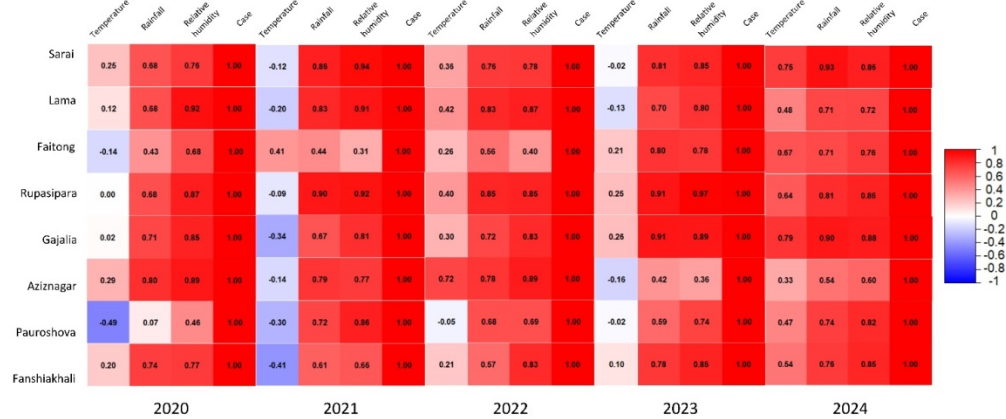
**Lagged Analysis:** To explore delayed effects of climatic variables on malaria incidence, lagged analyses (at 1-, 2-, and 3-month intervals) were performed. The results were visualised through heatmaps and further substantiated by significance testing.

**Time Series Decomposition:** This method was used to distinguish trends, seasonal cycles, and random fluctuations within both malaria and climate datasets, helping to uncover recurring transmission patterns.

**Hotspot Analysis:** The Getis-Ord  $G_i^*$  statistic was applied to Annual Parasite Index (API) data to identify statistically significant malaria hot spots and cold spots, based on contiguity-defined spatial relationships. This method enabled a more nuanced understanding of spatial clustering in malaria transmission.

**Results**

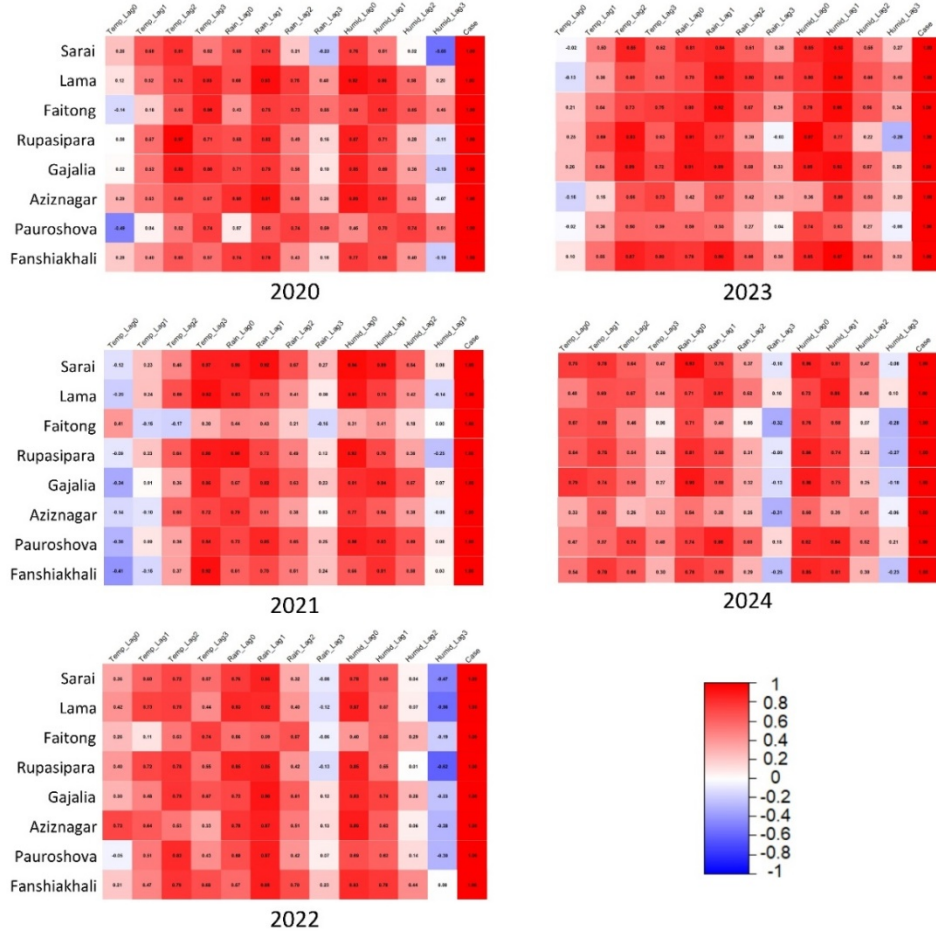
***Climatic Correlation with Malaria Incidence***



**Figure 3:** Spearman correlation heatmap of climatic parameters and malaria incidence

From 2020 to 2024, meteorological variables demonstrated differing levels of association with malaria incidence in the examined unions, with rainfall and humidity identified as the most reliable and statistically significant predictors. Rainfall exhibited notably robust associations in Sarai (0.93, p 0.0001), Rupasipara (0.91, p 0.0001), and Gajalia (0.91, p 0.0001), signifying its predominant impact on transmission patterns. Humidity exhibited strong relationships, particularly reaching peaks in Lama (0.92, p < 0.0001), Rupasipara (0.97, p < 0.0001), and Pouroshova (0.82, p = 0.0011). Conversely, temperature exhibited a more variable correlation, showing moderate associations in regions such as Sarai (0.75, p = 0.0047) and Gajalia (0.79, p = 0.0036), while displaying weak or even negative correlations in areas like Pouroshova and Lama. These findings highlight the crucial influence of rainfall and humidity as key climatic determinants of malaria risk, while the effect of temperature seems to be more context-dependent and less consistently predictive across regions.

Climatic Lag Correlation with Malaria Incidence

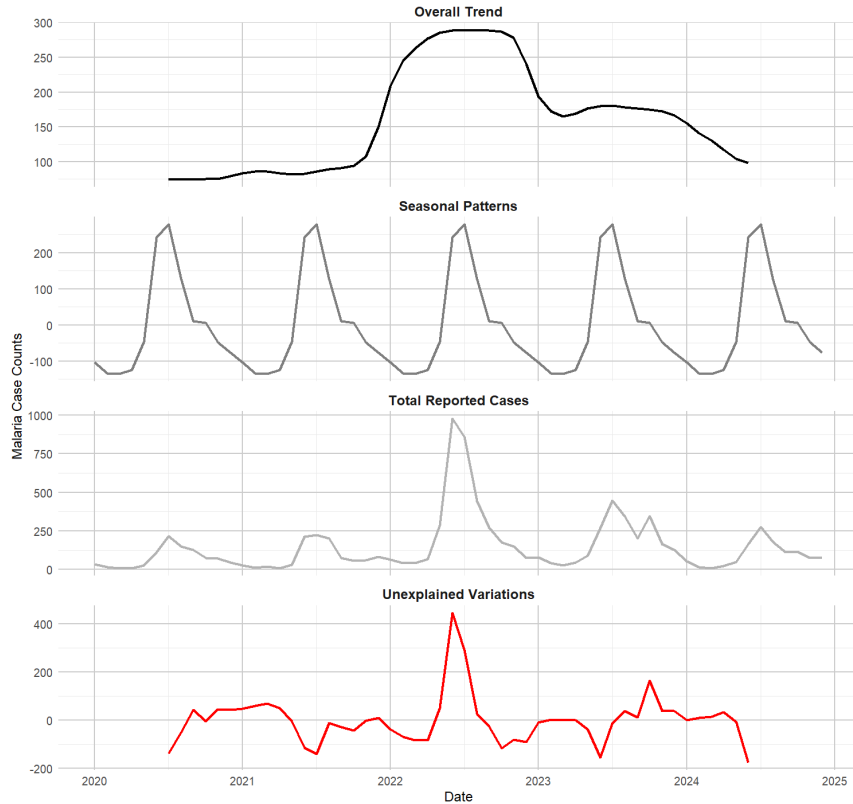


**Figure 4:** Spearman correlation heatmap of climatic parameters (1, 2, 3 month lag) and malaria incidence

Lagged correlation analysis for 2024 indicated that the most robust relationships between meteorological conditions and malaria incidence largely occurred at lag 1 across all unions, highlighting a brief temporal interval during which climatic changes most significantly affect transmission. Correlations among temperature, rainfall, and humidity were significantly elevated at lag 1, especially in Fanshiakhali (temperature: 0.78,  $p = 0.0047$ ; humidity: 0.81,  $p = 0.0025$ ), Sarai (humidity: 0.81,  $p = 0.0026$ ), and Lama (rainfall: 0.81,  $p = 0.0026$ ). Nonetheless, these correlations gradually diminished at delays 2 and 3, frequently becoming statistically insignificant or even negative—demonstrated by Sarai’s rainfall correlation decreasing from 0.75 at lag 1 to -0.10 at lag 3. This declining trend underscores the urgency of climate’s impact on malaria, indicating that early warning systems and control measures

should be implemented within a month following climatic abnormalities to successfully mitigate transmission surges.

**Time Series Analysis of Malaria Incidence**



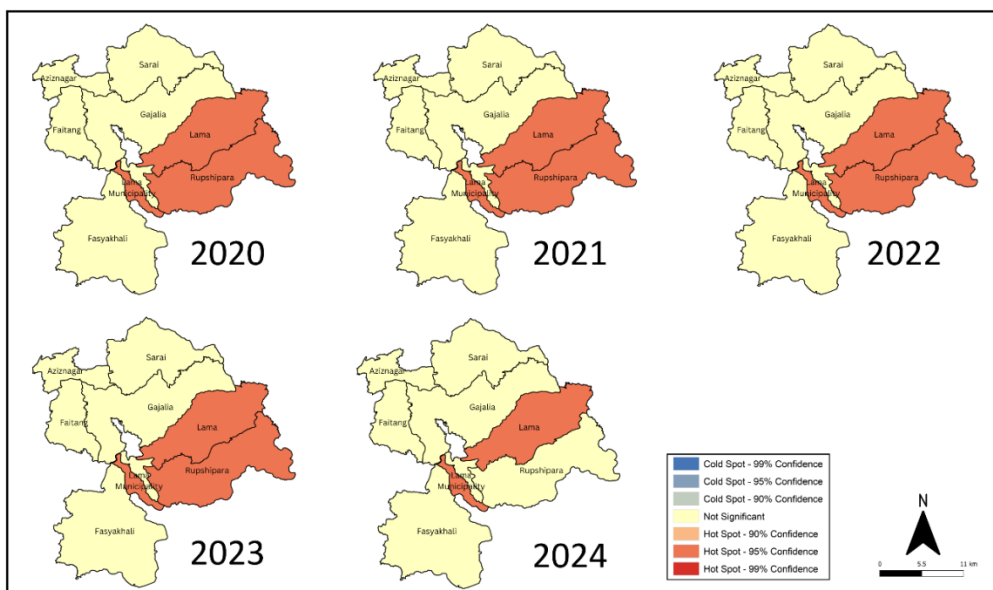
**Figure 5:** Time series decomposition of total malaria cases.

The time series study of malaria incidence from 2020 to 2024 indicated a complicated interaction of long-term trends, seasonal patterns, and stochastic fluctuations, with 2022 identified as a critical year due to a severe outbreak. The overall trend exhibited oscillations, with a significant increase in 2022, reaching a peak of 978 cases in June—signifying the third large outbreak in the last 12 years. This peak underscored the cyclical characteristics of malaria transmission and the region's susceptibility to intermittent surges. Subsequent to the 2022 epidemic, the incidence progressively diminished, stabilising in 2023 and 2024 at reduced levels, while not entirely returning to pre-outbreak baselines—illustrated by July 2024's 276 cases in contrast to 216 in July 2020. Seasonal decomposition highlighted the predictability of malaria outbreaks throughout the rainy season (June–September), with July consistently recording the greatest incidence across all years. The seasonal index reached its zenith in July 2022, coinciding with the outbreak and underscoring the critical influence of monsoon-related climatic factors on malaria dynamics. Nonetheless, the residual component

## *Climatic Determinants and Spatial Hotspots of Malaria Incidence*

revealed anomalies, particularly in 2022, where variations from anticipated trends suggested the presence of extra, unmeasured factors like pesticide resistance, strain on health systems, or behavioural changes. Year-on-year comparisons also demonstrated the anomalous nature of 2022, as instances nearly doubled compared to prior years before experiencing a steady decline in 2023 and 2024. Despite indications of stabilisation in 2024, the case count remained high relative to 2020, implying persistent post-outbreak repercussions. Collectively, our observations emphasise the necessity of incorporating climate-sensitive surveillance with contextual public health evaluations to proactively prevent and manage future outbreaks efficiently.

### **Identifying Malaria Hotspot**



**Figure 6:** Union-wise distribution of malaria hotspots.

The spatial study of malaria incidence in Lama Upazila from 2020 to 2024, utilising Getis-Ord  $G_i^*$  hotspot information, indicated a distinct and constant clustering of high-risk locations, with Lama and Rupshipara unions identified as enduring malaria hotspots. The regions marked in red, exhibiting confidence levels between 90% and 99%, regularly had high Annual Parasite Index (API) values—peaking at 73.74 in Lama and 80.71 in Rupshipara in 2022, coinciding with the district-wide outbreak. The persistent spatial clustering indicates that local environmental and infrastructural factors—such as extensive forestation, stagnant water bodies, and inadequate healthcare access—may foster optimal breeding and transmission conditions for malaria vectors. Temporal trends underscore this persistence; even during years of general decline, both unions sustained markedly elevated API levels, indicating endemic transmission patterns. In contrast, unions such as Sarai, Gajalia, Aziznagar, and sections of Lama Municipality were primarily classified as "Not Significant," represented in light yellow, signifying either intermittent or minimal transmission that lacks

spatial uniformity. The lack of statistically significant cold spots indicates that no place within the upazila consistently demonstrated very low or negligible malaria risk, highlighting the pervasive transmission potential throughout the region. This hotspot study offers vital evidence for spatially focused malaria control initiatives, indicating that ongoing surveillance, vector management, and community-orientated health interventions in Lama and Rupshipara are crucial for diminishing the overall malaria burden in Lama Upazila.

## Discussion

The results demonstrate the climate-malaria relationship and its regional manifestations by temporal correlation, spatial hotspot detection, and latency analysis. In Rupasipara (+0.94,  $p < 0.001$ ) and Gajalia (+0.92,  $p < 0.001$ ), precipitation emerged as the predominant predictor of malaria, with Lag 0 correlation coefficients surpassing +0.90, indicating that rainfall directly influences the creation of mosquito breeding habitats during the monsoon season (June–September). Approximately 65–75% of the yearly incidences transpired during this interval. Relative humidity values attained +0.91 at Rupasipara, signifying a substantial correlation, especially at Lag 0, which highlights its influence on vector survivability and activity during peak transmission periods.

Temperature exhibited more significant lagged associations, despite slight immediate effects (correlations  $< +0.50$ ). A delayed impact on parasite development and vector competence was noted in Lama Union, shown by a Lag 3 correlation of +0.70 ( $p < 0.05$ ). The average monthly temperature (24°C–32°C) consistently fell within the ideal transmission parameters during the study period. The findings align with studies in tropical areas, such as Sub-Saharan Africa and Mizoram, India, where malaria dynamics are jointly affected by temperature and precipitation (Parham & Michael, 2010; Lalmalsawma *et al.*, 2023).

Correlations diminished from +0.94 at Lag 0 to +0.52 at Lag 2, signifying a declining impact as stagnant water becomes progressively less conducive to breeding. The impact of precipitation was immediate. Conversely, temperature and humidity exhibited lagged effects. The correlation between temperature at Lags 2–3 was +0.68 to +0.73 ( $p < 0.01$ ), whereas relative humidity at Lag 3 attained +0.81 at Rupasipara ( $p < 0.001$ ). The observed lagged effects indicate a sequential process: rainfall triggers reproduction, which is then succeeded by delayed transmission affected by temperature and humidity. Documented in West Africa (Mafwele & Lee, 2022), these temporal delays—exemplified by the 387 mm of rainfall in July preceding the 612 cases in Lama during September—underscore the necessity for sustained post-monsoon treatments.

Lama and Rupasipara were repeatedly recognised as high-risk zones in the 2022 hotspot analysis, exhibiting peak API values of 73.74 and 80.71, respectively. The spatial clustering of these unions was significant (90–99% confidence), whereas others, like Aziznagar, displayed low, non-significant API levels (e.g., 0.42 in 2021). The absence of chilly regions indicated a widespread yet diverse malaria burden. These spatial variations underline the importance of regionally focused interventions aimed at addressing persistent locations. The results align with regional studies, especially in Mizoram ( $r = +0.75$  to  $+0.88$ ), where rainfall and temperature serve as the principal factors of the gearbox.

Unlike areas where elevated temperatures diminish vector viability, Lama's monsoon-affected and thermally moderate climate (25–30°C) may facilitate prolonged vector activity and postponed transmission. This work provides localised evidence to the global discussion on climate-sensitive malaria patterns, advocating for the creation of context-specific forecasting models and control techniques.

## **Conclusion**

The study revealed a strong positive association between rainfall and malaria incidence, alongside a moderate correlation between temperature and malaria incidence. Humidity had substantial correlations with malaria incidence. Between 2020 and 2024, Lama Upazila displays persistently high-risk areas marked by increased API values and spatial clustering of cases, highlighting the need for targeted malaria control strategies while maintaining extensive surveillance to manage malaria transmission intensity across the region.

Socioeconomic factors and healthcare accessibility may influence the incidence of malaria, including alterations in vegetation and aquatic environments. These indicators merit attention in future research.

## **Acknowledgement**

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*Climatic Determinants and Spatial Hotspots of Malaria Incidence*

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