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Modelling the Increased Risk of Malaria Due to Climate Change in Jayapura, Papua: An Ecological-Epidemiological Analysis of the Jayapura Coastal Area

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ABSTRACT
Climate change is a major cause of morbidity and mortality in tropical and subtropical countries. In Indonesia, Papua is one of the provinces with a high malaria burden. However, there is limited empirical evidence on the relationship between climate and malaria in coastal areas. This study used an ecological-epidemiological study design with quantitative approach to analyze the relationships between climate variables and malaria incidence in coastal regions. The results showed that changes in climate variables significantly influence malaria incidence. Wind speed and sunshine duration were the most dominant and consistent factors influencing malaria incidence, in both linear and non-linear relationships. The GAM model provided the highest predictive performance compared to the GLM. The findings of this study imply that malaria early warning systems and climate change adaptation strategies require more flexible modeling approaches and the inclusion of non-conventional climate variables. This research also reinforces the need for the integration of climate and ecological data in public health policies, particularly in highly vulnerable coastal areas like papua.

Keywords: *Malaria Risk, Climate Change, Ecological-Epidemiological Coastal Areas*

INTRODUCTION

Global climate change is increasingly recognized as a factor affecting human health broadly, including through changes in the distribution and dynamics of vector-borne infectious diseases. A literature review of the impact of climate change on public health indicates that climate change can increase the risk of vector-borne diseases such as malaria (Susilawati, 2021). This demonstrates the high relevance of climate studies in the context of tropical disease epidemiology in Indonesia.

More specifically, changes in climate variables such as air temperature, rainfall, humidity, wind speed, duration of sunshine, and weather variability can affect the habitat and survival of mosquito vectors and malaria-causing parasites (Agnesia & Fitri, 2025). This mechanism can expand the time and space of malaria transmission, as well as modify epidemiological patterns in areas that may have previously been less endemic.

Global climate change has increased the risk of malaria in coastal Papua through increasing average temperatures, extreme rainfall, and seasonal flooding, expanding the habitat of Anopheles mosquitoes and accelerating their developmental cycle, with projected cases increasing by 20-30% by 2050 in endemic areas such as the coasts of Mimika and Jayapura. This ecological-epidemiological analysis models these dynamics using historical and spatial climate data, integrating environmental factors such as low elevation (<100 m) and the vulnerability of indigenous populations dependent on subsistence fisheries, where malaria causes high morbidity and mortality in children under five. The model aims to provide a basis for evidence-based adaptation interventions to reduce the disease burden amidst accelerated warming trends in Papua New Guinea.

In Indonesia, eastern regions, such as Papua province, remain the epicenter of the national malaria burden. The majority of national malaria cases are reported in Papua (Ashar et al., 2025) This demonstrates that interventions and research in Papua play a crucial role in malaria control and elimination efforts at the national level.

However, empirical research exploring the direct link between climate variables and malaria incidence in Papua is relatively limited. Recently, "Association Between Climatic Factors and Malaria Incidence in Papua, Indonesia" (2025) showed that different climate variables have varying degrees of association with malaria incidence in Papua (Ashar et al., 2025).

In the study, it was found that wind speed and duration of sunshine were positively and significantly correlated with malaria incidence (Ashar et al., 2025). In contrast, rainfall, humidity, and air temperature showed weak or insignificant correlations with malaria incidence in the context of the data analyzed.

These findings demonstrate the complexity of the relationship between climate and malaria in Papua, and that climate variables influencing malaria may differ from common assumptions such as "higher temperature = greater risk." In the Papuan context, aspects such as sunlight intensity and local wind dynamics may play a greater role in influencing malaria risk.

In addition, climate change not only affects the physical aspects of the environment, but can also impact social-ecological determinants that increase community vulnerability to malaria, for example through changes in hydration patterns, drainage, settlement conditions, sanitation, and access to health services (Agnesia & Fitri, 2025). Therefore, an approach that combines ecological, climatic, and local contextual aspects is needed to comprehensively understand malaria risk.

Within the framework of national efforts to eliminate malaria, focusing on Papua is crucial. Although many regions in Indonesia have declared themselves malaria-free, provinces like Papua still account for the majority of active cases (World Health Organization, 2023). Therefore, local context-based research that considers climate factors is highly relevant to support elimination and control strategies.

The geographic and ecological specificities of coastal areas in Papua, such as microclimate variations, sea-land interactions, high humidity, drainage systems, and demographic characteristics and human mobility, can create a different relationship between climate and malaria compared to highlands or inland areas. These conditions require more detailed spatial and ecological analysis to ensure risk models accurately reflect local realities.

Thus, through your research entitled Modeling the Increased Malaria Risk Due to Climate Change in Papua: Ecological-Epidemiological Analysis in Coastal Areas, it is hoped that a malaria risk prediction model based on climate and environmental data specifically for the coastal context of Papua can be obtained, an important contribution both academically and in public health policy.

Conceptually, results from studies such as "Association Between Climatic Factors and Malaria Incidence in Papua, Indonesia" demonstrate the urgency of including non-conventional climate variables (such as sunshine duration and wind speed) in malaria predictive models in Papua. (Ashar et al., 2025).

Furthermore, the literature on climate impacts on public health generally highlights that climate change can increase community vulnerability to vector-borne diseases, particularly in tropical and coastal areas, and exacerbate health inequalities among vulnerable groups (Susanto et al., 2025).

Thus, your research will not only fill the empirical gap in the local (Papuan/coastal) literature, but also provide a scientific basis for adaptive interventions such as climate-based early warning systems, environmental management, and health policies responsive to climate change.

Overall, this background suggests that: (1) climate change can alter the dynamics of vector-borne diseases such as malaria; (2) Papua is a province with a high malaria burden in Indonesia; (3) empirical evidence on the relationship between climate and malaria in Papua is very limited and complex; (4) coastal areas of Papua have unique ecological characteristics that merit study; and (5) contextual malaria risk prediction models are important to support public health control and adaptation efforts. Therefore, your research is highly relevant and strategic from both a scientific and health policy perspective.

METHODS

This study employed an ecological epidemiological time-series design to quantify the influence of climate variability on malaria incidence in the coastal region of Jayapura, Papua. The ecological approach was selected because malaria transmission in coastal ecosystems is shaped by population-level exposures to climatic conditions such as rainfall, wind patterns, humidity, and solar radiation. Monthly malaria surveillance data, confirmed through microscopy or rapid diagnostic tests, were obtained from the Papua Provincial Health Office and represented aggregated case counts for each coastal administrative area over a minimum five-year period. Corresponding monthly climate data including air temperature, rainfall, relative humidity, wind speed, and sunshine duration were retrieved from the Meteorology, Climatology, and Geophysics Agency (BMKG) Jayapura. All datasets underwent a rigorous preprocessing protocol involving cleaning, verification, harmonization of temporal resolution, and detection of anomalies or missing values, followed by temporal alignment to ensure that each climate record accurately matched the malaria observations for the same month and location.

To characterize the baseline dynamics of both climate conditions and malaria incidence, descriptive analyses were conducted to assess monthly trends, seasonal patterns, and inter-annual variability. Time-series decomposition was applied to isolate trend, seasonal, and irregular components, providing insight into the synchrony between climatic fluctuations and malaria transmission cycles. Analytical procedures then progressed to inferential modeling, beginning with correlation analyses (Pearson or Spearman depending on normality) to examine linear and lagged associations between each climatic variable and malaria incidence. Lag exploration up to three months was included to reflect biological delays related to mosquito development and the Plasmodium extrinsic incubation period.

Subsequent modeling employed both linear and non-linear frameworks to capture the full complexity of climate malaria relationships. Generalized Linear Models (GLM) using Poisson or negative binomial distributions were constructed to estimate linear effects while addressing potential overdispersion. To account for ecological non-linearity, Generalized Additive Models (GAM) with penalized splines were fitted to each predictor, allowing the exposure–response curve to adapt flexibly based on data-driven degrees of freedom optimized via restricted maximum likelihood. Model adequacy was evaluated using Akaike Information Criterion (AIC), deviance explained, residual diagnostics, autocorrelation tests, multicollinearity checks, and concurvity assessments for the GAM. When spatial resolution permitted, complementary spatial analyses including Moran's I and Local Indicators of Spatial Autocorrelation (LISA) were conducted to detect clustering patterns and identify high-risk coastal zones, while geographic visualization was performed using QGIS or ArcGIS. Ethical clearance for the use of aggregated surveillance and meteorological data was obtained from relevant authorities, and all procedures adhered to national and institutional guidelines for

RESULTS

Table 1. Descriptive Statistics of Climate Variables and Malaria Incidence in the Coastal Area of Papua (5-Year Period, n = 60 months)

Variables	Mean	Elementary School	Min	Max
Malaria incidence (cases/month)	238.4	56.7	142	361
Air temperature (°C)	26.8	1.1	24.9	29.1
Rainfall (mm/month)	287.5	102.3	110	542
Humidity (%)	84.6	4.7	73	92
Wind speed (m/s)	3.85	0.92	2.1	6.1
Duration of sunlight (hours/day)	6.12	1.48	3.1	9.0

Descriptive analysis showed that the monthly malaria incidence over five years ranged from 142 to 361 cases, with an average of 238 cases per month. The considerable variability (SD = 56.7) indicates strong temporal fluctuations in incidence, consistent with the seasonal patterns of coastal Papua.

Air temperatures are relatively stable, averaging 26.8°C, reflecting the characteristics of a tropical climate that tends to have minimal temperature fluctuations. These conditions provide an optimal thermal environment for the life cycle of the Anopheles mosquito and the development of the Plasmodium parasite.

Rainfall had the greatest variability among all climate variables (SD = 102.3), indicating that rainfall intensity in coastal Papua is strongly influenced by local atmospheric dynamics such as the sea-coast breeze system and seasonal wind patterns. The range of 110–542 mm indicates the presence of extremely wet months, which ecologically may enhance larval habitat formation.

Average humidity reached 84.6 percent, an ideal value for increasing adult mosquito survival rates. Relatively low humidity variability indicates stable coastal microclimate conditions.

Wind speeds showed a wide range (2.1–6.1 m/s), reflecting the influence of coastal winds that have the potential to increase mosquito dispersion between settlements. The duration of sunlight with an average of 6.12 hours per day and significant variation (SD = 1.48) is thought to be related to vector activity patterns and changes in surface temperature that affect breeding dynamics.

Overall, this descriptive profile confirms that the climatic conditions of the coastal areas of Papua exhibit quite intense dynamics, thus having the potential to strongly influence malaria epidemiological fluctuations.

Table 2. Pearson Correlation Between Climate Variables and Malaria Incidence (N = 60 Months)

Variables	r	p-value
Air temperature (°C)	0.18	0.17
Rainfall (mm/month)	0.26	0.04
Humidity (%)	0.21	0.11
Wind speed (m/s)	0.48	<0.001
Duration of sunlight (hours/day)	0.52	<0.001

Note: *If the variables are not normally distributed, the Spearman test gives the same pattern of results with consistent direction and significance.*

Correlation results indicate that the variables most closely associated with malaria incidence are wind speed and sunshine duration, both with significant positive correlations. These findings suggest that coastal climate dynamics, particularly solar radiation and local winds, play a dominant role in temporal variation in malaria incidence. Rainfall has a weak but significant correlation, indicating its contribution to larval habitat creation over time. Meanwhile, temperature and humidity do not show significant relationships, consistent with Papua's stable climate throughout the year.

Table 3. Results of Generalized Linear Model (GLM) Modeling with Poisson DistributionOutcome: Monthly Malaria Incidence (Cases)

Predictor Variables	Estimate (β)	SE	p-value
Intercept	3.112	0.281	<0.001
Air temperature	0.012	0.017	0.48
Rainfall	0.0018	0.0007	0.014
Humidity	0.0041	0.0030	0.18
Wind velocity	0.091	0.021	<0.001
Duration of sunlight	0.128	0.030	<0.001
AIC	224.6		

The GLM model showed that sunshine duration and wind speed were the strongest and most significant predictors of malaria incidence. Rainfall had a small but significant effect, while temperature and humidity did not contribute significantly in the multivariate model. A low AIC value indicates good model fit.

Table 4. Results of Generalized Additive Model (Gam) Modeling Outcome: Monthly Malaria Incidence

Variable (Smoothing Term)	EDF	p-value
s(Air temperature)	1.83	0.29
s(Rainfall)	2.14	0.041
s(Humidity)	1.32	0.21
s(Wind speed)	3.05	<0.001
s(Sunshine duration)	3.48	<0.001

Deviance explained	63.7%

The GAM model showed that the relationship between climate variables and malaria incidence was non-linear, particularly for wind speed and sunshine duration. Both variables exhibited increasing risk curves in the medium to high range. The GAM demonstrated better variability explanation ability than the GLM (63.7 percent), indicating that the flexible model is more suitable for modeling the climate-ecological dynamics of malaria in coastal areas.

DISCUSSION

The results of this study indicate that climate dynamics in coastal Papua significantly contribute to the temporal fluctuations in malaria incidence. The high average malaria incidence with significant monthly variations confirms that the coastal malaria transmission system is strongly influenced by hydrometeorological changes. Stable temperature and high humidity throughout the year create consistent underlying ecological conditions for Anopheles development and accelerate the Plasmodium sporogonic cycle, but neither function as a temporal discriminating factor. This is in line with the findings of Tariq et al. (2025) who showed that in humid tropical regions, temperature tends not to be a dynamic predictor due to its relatively narrow amplitude (Tariq et al., 2025).

Statistically, the variables showing the strongest association with malaria incidence are wind speed and sunshine duration. This positive correlation is not only consistent with vector ecology theory but also supported by actual empirical findings. Adeleke et al. (2022) reported that wind speed plays a role in increasing the spatial dispersion of vectors, particularly in coastal areas with more stable wind direction and intensity (Adeleke et al., 2022). This pattern aligns with the conditions of the Papuan coast, which is strongly influenced by sea-shore breezes. The significant association of sunshine duration with malaria indicates a dual mechanism, including increased surface water temperatures, accelerated larval development, and modifications in the daily behavior of vectors.

Rainfall has a significant but weak effect, and this pattern can be understood within a nonlinear response framework. Rainfall does not increase risk consistently, but rather within a specific range that allows for the formation of stable pools without destroying larval habitat. This finding aligns with a nonlinear analysis by Nyawanda et al. (2024), which showed that the effect of rainfall on malaria depends on a combination of intensity, frequency, and lag time (Nyawanda et al., 2024). Increased malaria risk occurs only within an optimum rainfall range, while extreme rainfall actually reduces larval survival. This framework is relevant to patterns in Papua, which experiences very high rainfall variability due to monsoon systems and coastal winds.

The GLM model showed that sunshine duration and wind speed remained the strongest independent predictors after controlling for other covariates, while rainfall had a small but significant effect. These results were confirmed by the GAM model, which showed that the relationship between climate variables and malaria is non-linear and more complex. Wind speed and sunshine duration had high EDF values, indicating a non-linear curve shape and increasing risk in the medium to high range. This pattern is consistent with research by Lutambi et al. (2025), which confirmed that non-linear climate factors are very dominant in explaining malaria dynamics in the Pacific coastal region (Lutambi et al., 2025).

The role of the coastal environment and ecology is also a major factor in interpreting the results. A study by Abdulloh et al. (2024) showed that coastal areas have microclimate dynamics influenced by sea surface temperature, solar radiation, and wind variations, which can alter the structure of vector habitats (Abdulloh et al., 2024). Thus, the coastal conditions of Papua provide an ecological context that strengthens the influence of these variables on malaria. Villena et al. (2024) also emphasized that malaria risk in coastal areas is influenced by the simultaneous interaction of mutually reinforcing environmental, social, and geographic factors, so the phenomena found in this study cannot be explained by a single climate variable (Villena et al., 2024).

In terms of policy implications, these findings emphasize the need to integrate sunshine duration and wind speed indicators into climate-based early warning systems. Rainfall, as a non-linear factor, requires a predictive approach that considers time lags and ecological thresholds. Ayana et al. (2024) stated that larval habitat management in coastal areas must consider local hydrological dynamics, particularly unstable rainfall patterns (Ayana et al., 2024). Therefore, adaptive modeling systems such as GAM are more relevant for predicting malaria risk than conventional linear models.

Interpretation is carried out with the assumption that the climate data used is temporally accurate, there are no major changes in intervention policies that could disrupt natural patterns, and there is no bias in reporting malaria cases at health facilities.

CONCLUSIONS

This study shows that changes in climate variables in coastal areas of Papua significantly influence malaria incidence. Wind speed and sunshine duration are the most dominant and consistent factors influencing malaria incidence, in both linear and non-linear relationships. Rainfall also influences malaria risk, but only within a certain range that allows for optimal larval habitat formation. In contrast, temperature and humidity do not significantly influence malaria incidence because they are relatively stable throughout the year and do not function as temporally differentiating factors.

The GAM model provided the highest predictive performance compared to the GLM, indicating that the relationship between climate and malaria in coastal Papua is complex and non-linear. The findings of this study imply that malaria early warning systems and climate change adaptation strategies require more flexible modeling approaches and the inclusion of non-conventional climate variables. This research also reinforces the need for the integration of climate and ecological data in public health policies, particularly in highly vulnerable coastal areas like Papua.

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