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# Malaria Incidence Dynamics in the Context of Expanded Seasonal Chemoprevention in Mali, 2016–2018

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## Abstract

In Mali, malaria exhibits strong seasonality, posing significant health risks to young children. To reduce this burden, Seasonal Malaria Chemoprevention (SMC) has been introduced, which entails providing monthly doses of antimalarial medication to children aged 3–59 months over a four-month period coinciding with peak malaria transmission. This study investigated changes in malaria incidence in the general population across the health districts of Kadiolo, Kati, Yorosso, Sikasso, and Tominian during the rollout of SMC. We conducted a cross-sectional analysis using routine malaria case data combined with meteorological records from Nasa Giovanni for 2016–2018. The relationship between malaria incidence and climate variables was assessed using Generalized Additive Models (GAMs). Over the three-year period, malaria incidence in all districts was positively linked to relative humidity, rainfall, and minimum temperatures. While relative humidity and monthly incidence varied between districts, average temperature and rainfall were relatively uniform. A reduction in malaria cases among children under five was observed in 2017 and 2018 compared to 2016. The SMC program coincided with a decline in malaria incidence among young children, highlighting its potential effectiveness. Strategic timing of SMC administration is crucial to achieve optimal protection during peak transmission periods.

**Keywords:** Malaria, Incidence, Mali, Seasonal malaria chemoprevention

## Introduction

Malaria remains one of the most widespread parasitic diseases globally, with over half of the world's population living in at-risk areas. Despite significant advances in prevention and control, it continues to challenge health systems worldwide [1]. In Mali, malaria is the leading cause of medical consultations during peak transmission periods. Data from the National Health Information System (SNIS) indicate that 2,345,481 malaria cases were recorded in health facilities in 2018, making it the top cause of death that year with 1,178 fatalities [2].

Mali's territory spans five climatic zones: the pre-Guinean zone (annual rainfall >1,100 mm), Sudanian (900–1,100 mm), Sudano-Sahelian (500–900 mm), Sahelian (250–500 mm), and the Sahara desert (<250 mm), along with the inner Niger River delta. These climatic and geographic features contribute to malaria being a major public health concern across most of the country.

To combat malaria, the Malian government, through the National Malaria Control Program (NMCP), has implemented multiple interventions, including case diagnosis and treatment, epidemiological monitoring, vector control using insecticide-treated nets and indoor residual spraying, and chemoprevention for vulnerable populations [3, 4]. These measures follow WHO recommendations. Among them, Seasonal Malaria Chemoprevention (SMC) targeting children aged 3–59 months is recognized as a cost-effective, safe, and efficient strategy [5].

Evidence from studies in the districts of Sadiola and Segou indicates that indoor residual spraying can reduce malaria cases by up to 70% [6, 7]. Regarding chemoprevention, the NMCP advises administering Sulfadoxine–Pyrimethamine with Amodiaquine (AQ-SP) to children, while pregnant women receive intermittent preventive treatment with SP (three tablets monthly starting in the second trimester) [5, 8, 9]. Since 2012, WHO has recommended SMC in Sahelian countries, where the majority of malaria cases occur within a brief four-month period [5, 8, 9].

The SMC program involves providing a single dose of SP plus a three-day course of Amodiaquine, repeated over four monthly rounds for children aged 3–59 months, and more recently extended to children aged 5–10 years [10, 11]. Pilot studies in Mali have shown notable reductions in malaria and anemia among children, with a 40% decrease in confirmed malaria cases reported in observational analyses [12, 13]. Similar positive results have been observed in Mali, as well as in neighboring countries such as Ivory Coast and Senegal [11, 13–15].

A study conducted in Ouessebougou examined IgG antibodies against malaria antigens following SMC. While antibody levels did not directly correlate with the number of SMC rounds received, children who participated in the program exhibited higher IgG levels compared to those who did not [16].

Despite these interventions, malaria continues to impose a significant burden on the population. In response, the NMCP, in collaboration with the Malaria Research and Training Center (MRTC) and with World Bank support, initiated a study to track malaria incidence in the context of SMC scale-up. Our secondary analysis focused on five districts — Kati, Sikasso, Kadiolo, Yorosso, and Tominian — representing diverse epidemiological contexts, including border regions. By analyzing routine health system data, this work aims to monitor trends in malaria incidence and inform the NMCP on how to optimize and target SMC interventions effectively.

**Materials and Methods**

The study protocol received approval from the Ethics Committee of the Faculty of Medicine and Odonto-Stomatology and the Faculty of Pharmacy at the University of Techniques, Technologies, and Sciences of Bamako (Approval No. 2017__131__/CE/FMPOS), with all applicable regulatory requirements fulfilled. Measures were taken to ensure the confidentiality and anonymity of participants and all study documents.

*Population and study location*
This research was carried out across five health districts in Mali, each representing distinct malaria transmission settings, and was funded by the World Bank as part of the Neglected Tropical Diseases (NTD) and Malaria initiative. The districts included:
Kati: Approximately 15 km northwest of the capital, Bamako.
Kadiolo: Located about 470 km south of Bamako, at the country's southern extremity.
Sikasso: Situated roughly 370 km from Bamako in southern Mali.
Tominian: About 464 km northeast of Bamako, in the Segou region.
Yorosso: Located nearly 426 km from the capital.
Climatic data for these districts, including temperature and rainfall patterns from 2016 to 2018, are detailed in **Table 1.**

**Table 1.** Rainfall and temperature characteristics of the study sites, 2016–2018.

| Health District | Average Annual Temperature (°C) | Average Annual Rainfall (mm) |
|---|---|---|
| **Kati** | 30 | 789.6 |
| **Kadiolo** | 27.6 | 1000 |
| **Sikasso** | 27 | 1100 |
| **Tominian** | 30 | 500 |
| **Yorosso** | 28 | 681.7 |

Based on Mali's climatic classification, the study sites are situated within the Sahelian and Sudanian zones (Kati and Tominian, respectively) and the South Guinean zone (Yorosso, Kadiolo, and Sikasso) **(Table 1)** [17, 18]. The districts of Tominian, Kati, and Yorosso receive between 800 and 500 mm of annual rainfall, with average temperatures of 30 °C in Kati and Tominian. In contrast, the southern districts of Sikasso and Kadiolo experience more humid conditions, with annual rainfall exceeding 1,000 mm.

*Sources and data*
This cross-sectional study analyzed routine malaria surveillance data from five health districts: Kati, Sikasso, Kadiolo, Yorosso, and Tominian. All confirmed malaria cases, diagnosed either by rapid diagnostic tests (RDTs) available at health centers or by thick smear at health facilities, were collected through monthly reports and recorded in the District Health Information Software

(DHIS2, version 2). Monthly malaria data from the study districts during the study period were extracted from the validated DHIS2 databases and monthly malaria reports. Meteorological data, including mean, minimum, and maximum temperatures, relative humidity, and cumulative rainfall, were obtained from the Nasa Giovanni platform (https://giovanni.gsfc.nasa.gov/giovanni/) for all five districts. All data were aggregated on a monthly basis.

For analyzing the relationship between malaria incidence and meteorological factors, the health districts were grouped according to Mali's climatic zones. Two primary zones were considered: the Northern Sudan and Sahel zones as one group, and the Sudan-Guinean zone as the second group. Additional climate data were collected from Nasa Giovanni according to these zone classifications.

*Data analysis*

To evaluate malaria patterns, we examined annual incidence across the five health districts from 2016 through 2018. The relative change in malaria incidence over this period for each district was determined using the WHO-recommended formula:

$$\text{Rate variation} = (\text{Annual incidence } (_{2016}) - \text{Annual incidence } (_{2018}))/\text{Annual incidence } (_{2016}) * 100 \quad (1)$$

Meteorological and malaria data were analyzed on a monthly timescale. Descriptive statistics and graphical representations were used to summarize monthly malaria cases alongside rainfall, temperature, and relative humidity from 2016 to 2018. Comparisons of average monthly meteorological values between districts were conducted using ANOVA and the Kruskal–Wallis nonparametric test.

To explore how climate influenced malaria incidence, we first applied Principal Component Analysis (PCA) to reduce the number of meteorological variables while accounting for correlations among them [19]. Following this, we implemented a Generalized Additive Model

(GAM) to quantify the relationship between malaria incidence and meteorological factors [20]. Given the overdispersion observed in malaria counts, the negative binomial distribution was employed. Population data were log-transformed to calculate district-level malaria risk ratios, and the presence of SMC interventions was included as a covariate. The GAM was selected because malaria incidence exhibits nonlinear behavior, with clear seasonal trends and temporal fluctuations [21]. A p-value of $\leq 0.05$ was considered statistically significant.

The model was expressed as:

$$\log(\text{Cases}(T)) = \log(\text{Population}(T)) + f_1(\text{Dim1}) + f_2(\text{Dim2}) + \varepsilon \quad (2)$$

*Packages and software*

All statistical analyses were conducted using R software (version 3.4; R Foundation for Statistical Computing, R Development Core Team, Vienna, Austria) with the packages FactoMineR, Factoextra, and mgcv. Image processing was performed using Paint.net (version 4.2.13; Warren Color and Paint Co., Nashville, TN, USA).

## Results and Discussion

*Malaria incidence patterns in the five health districts*

Monthly malaria data from 2016 to 2018 indicated a clear seasonal pattern, with cases rising from July through November in all five health districts, coinciding with the rainy season. While overall incidence showed a downward trend during the study period, Yorosso and Sikasso districts did not follow this pattern. In contrast, from January to June, malaria cases were generally lower across the population, highlighting the seasonal nature of transmission. The peak transmission period was longer in the Sudano-Guinean districts of Yorosso, Sikasso, and Kadiolo, lasting approximately five to six months (June–November), whereas in Tominian and Kati, located in the northern Sahelian and Sudanian zones, it spanned four to five months **(Figures 1 and 2).**
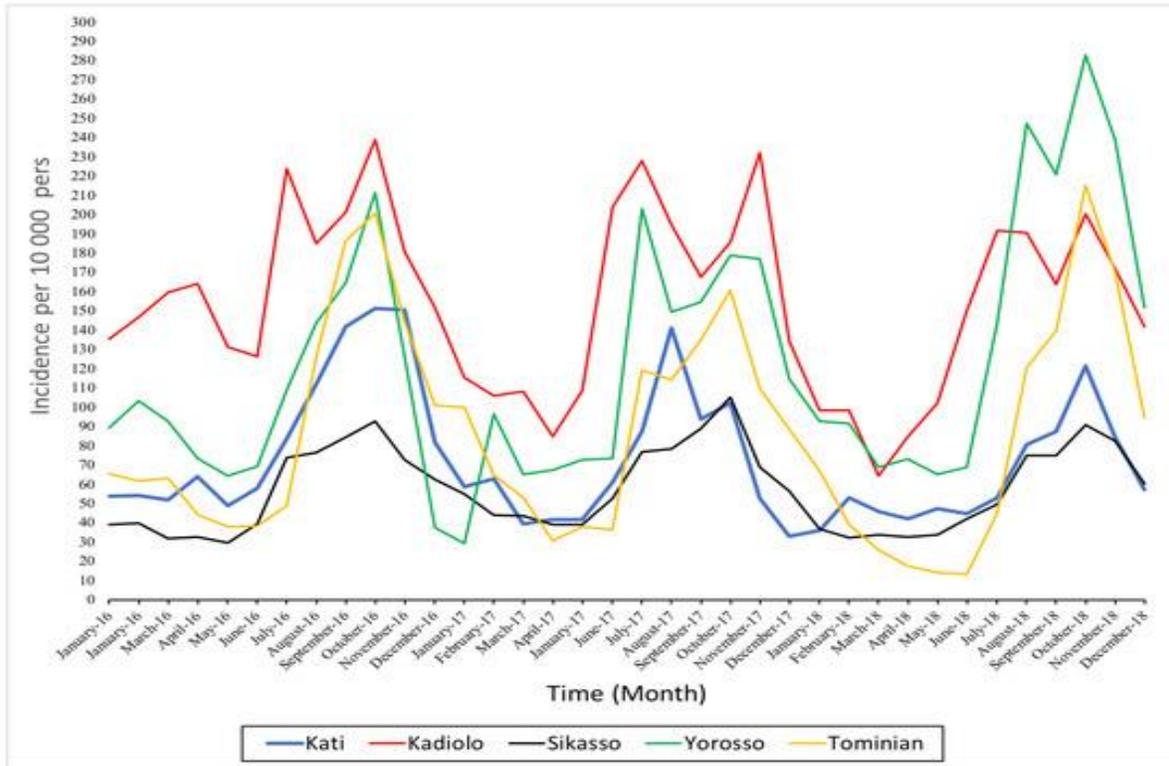
**Figure 1.** Monthly trends in malaria incidence across the five health districts, 2016–2018.
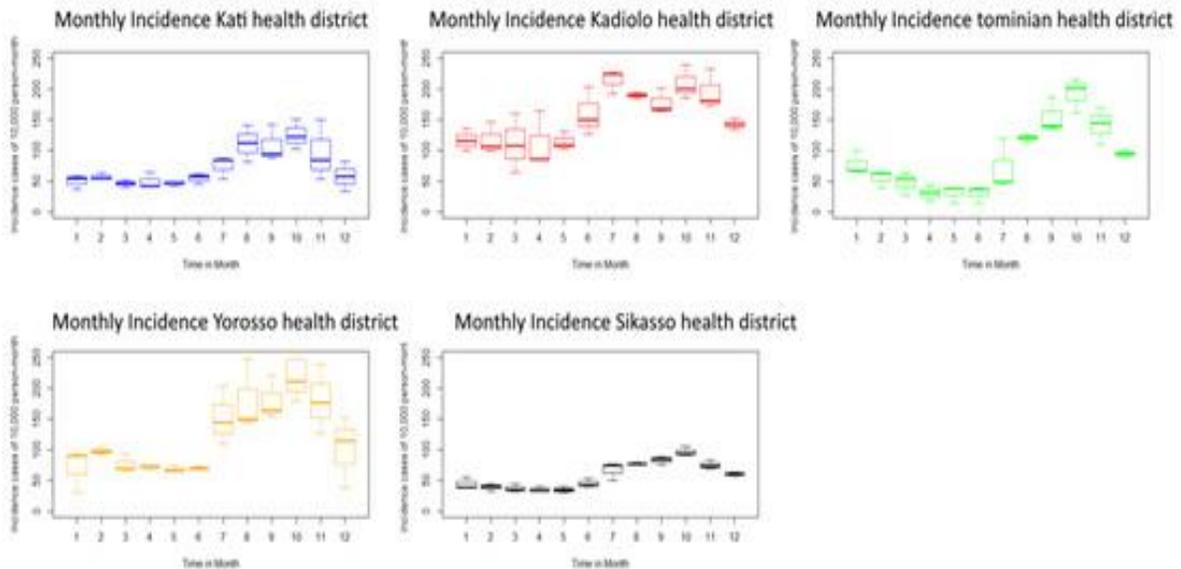


**Figure 2.** Average monthly malaria incidence per 10,000 population across the five health districts, 2016–2018.

Analysis of monthly malaria data from the five districts revealed a pronounced seasonal pattern, with case numbers peaking during the rainy season, typically between July and December, and occasionally extending into January. Following this period, malaria incidence consistently declined.

Among the districts, Yorosso, Kadiolo, and Tominian exhibited the highest monthly average incidence, ranging from 160 to 290 cases per 10,000 population.

Conversely, Kati and Sikasso experienced lower rates overall. October represented the peak month for Kadiolo and Yorosso, with median incidences of 200 and 210 cases per 10,000 population per month, respectively, while Sikasso recorded the lowest median incidence at 50 cases per 10,000 population per month.

*Age-specific monthly malaria incidence and smc timing*
Throughout the study period (2016–2018), children under five consistently experienced higher monthly malaria incidence than those aged five years and older across all five districts. Case numbers were lowest in the dry season and highest during the rainy season, with both age groups typically reaching peak incidence between July and October. Seasonal Malaria Chemoprevention (SMC) campaigns were implemented from August to November in 2016 and from July to October in 2017 and 2018. However, noticeable reductions in malaria incidence were primarily observed following the third and fourth rounds of SMC. The period of heaviest rainfall, generally occurring in July and August, coincided with SMC administration, while monthly incidence peaks were mostly recorded toward the end of the rainy season, in September and October. These patterns indicate that SMC interventions were consistently deployed after the onset of the high-transmission season in all districts.

The relative change in malaria incidence between 2016 and 2018 at the five study sites was calculated in accordance with WHO guidelines.
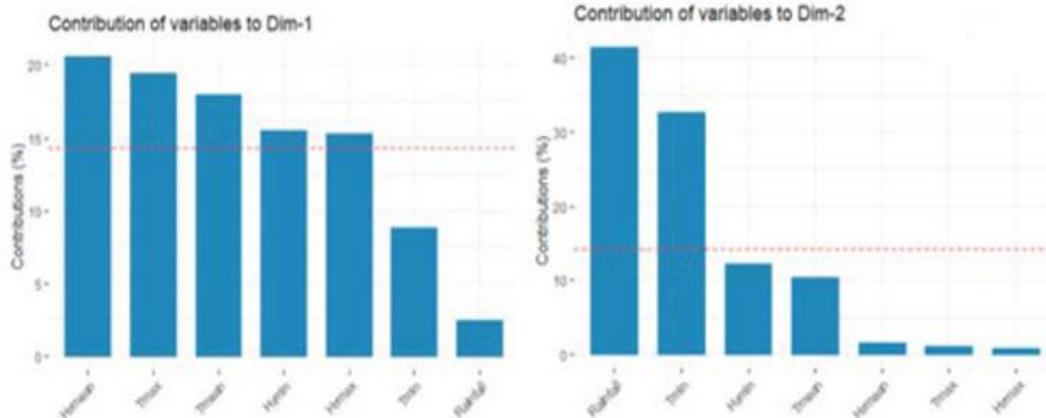
*Malaria incidence in relation to meteorological variables*
   *Uunivariate analysis*
Each district's meteorological data were examined individually to explore their association with malaria incidence.

   *Multivariate analysis*
Principal Component Analysis (PCA) was applied to reduce the meteorological dataset into two main dimensions, which together accounted for over 80% of the variability. The first dimension (Dim-1) captured relative humidity, with average and maximum temperatures contributing inversely. The second dimension (Dim-2) primarily reflected minimum rainfall and temperature within the same climatic zone **(Figure 3)**. In the Sahelian districts, rainfall contributed more to Dim-2 (40%) than minimum temperature (30%) **(Figure 3a),** whereas in the Sudano-Guinean districts, minimum temperature had a greater influence than rainfall for this dimension **(Figure 3b).**



a)
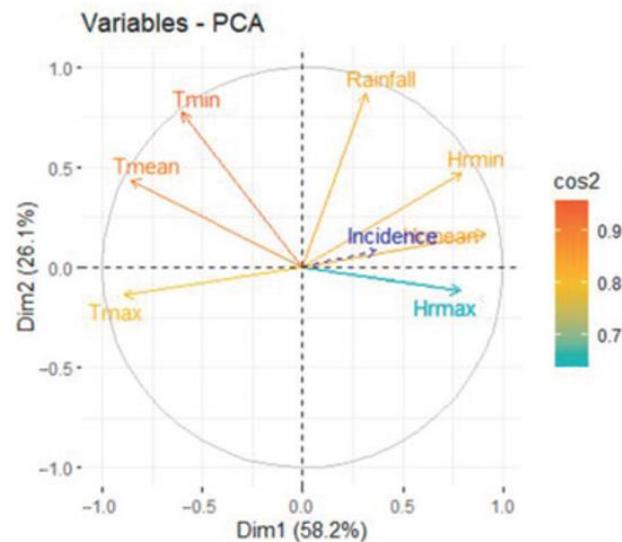
b)

**Figure 3.** Contribution of meteorological variables to PCA: (a) Sahel zone; (b) Sudano-Guinean zone.

To examine the joint effects of climatic factors on malaria incidence, we applied a Generalized Additive Model (GAM) using the principal components derived from the PCA for each climatic region. By combining the meteorological variables into these components, we could evaluate their collective influence on malaria transmission in the two zones.

In both climatic zones, the first principal component (Dim-1) reflected relative humidity positively while incorporating maximum and average temperatures negatively. The second component (Dim-2) primarily represented minimum and rainfall temperature. In the Sahel zone and Northern Sudan, Dim-2 showed a significant linear association with overall malaria incidence (p < 0.001), accounting for 74% of the explained deviance in the multivariate model **(Table 4)**.

In the Sudano-Guinean zone, Dim-2, again composed mainly of minimum and rainfall temperature, was significantly linked to malaria incidence (p < 0.001). Dim-1 followed the same pattern of negative contributions and positive relative humidity from average maximum temperatures. In this zone, the model explained 50% of the deviance **(Table 4)**.

One limitation of this study was the inability to account for time lags between overall malaria incidence and meteorological factors, as only monthly data were available and weekly data were not accessible. Additionally, specific coverage rates of malaria control

interventions—such as ownership and use of long-lasting insecticidal nets (LLINs) and SMC coverage—could have helped explain some of the observed differences in incidence trends across the health districts, although LLIN usage was assumed to be similar across all districts. The primary aim of this study was to examine trends in malaria incidence within the general population of the five health districts (Kadiolo, Kati, Yorosso, Sikasso, and Tominian) using routine data, and to assess the relationship between environmental factors and malaria incidence, including relative humidity, temperature, and rainfall, in the context of evaluating the impact of Seasonal Malaria Chemoprevention (SMC) from 2016 to 2018.

Analysis of monthly malaria incidence revealed that the peak transmission period coincides with the rainy season and the formation of water collections such as ponds and reservoirs, creating optimal conditions for mosquito breeding. This pattern likely explains the pronounced increase in malaria cases observed in all five districts, with the highest incidence generally occurring between July and October.

Compared with 2016, malaria incidence declined in 2017 and 2018 in all districts except Yorosso **(Table 2)**. This reduction may be attributable to the door-to-door SMC delivery strategy introduced by the NMCP in 2017, which likely achieved higher coverage than the previously used fixed-site approach.

**Table 2.** Percentage change in malaria incidence between 2016 and 2018.

| Health District | Rate Variation (%) | Sum of Annual Cases | | |
|---|---|---|---|---|
| | | 2016 | 2017 | 2018 |
| **Yorosso** | −43.99 | 34,511 | 38,274 | 49,692 |
| **Kadiolo** | 14.11 | 62,314 | 58,614 | 53,522 |
| **Sikasso** | −1.16 | 41,720 | 47,620 | 42,206 |
| **Kati** | 24.14 | 66,781 | 53,276 | 50,660 |
| **Tominian** | 8.91 | 31,096 | 30,033 | 28,325 |

The percentage change in malaria incidence between 2016 and 2018 indicates a decline in three health districts—Kati, Kadiolo, and Tominian.

Among the five districts, Kadiolo consistently recorded the highest incidence rates, followed by Tominian, Yorosso, Kati, and Sikasso. The length of the peak transmission period varied between districts, reflecting the influence of ecological factors on malaria dynamics. Previous studies in Mali and other regions have similarly reported higher malaria incidence during the rainy season. For instance, Dolo *et al*. (2003) observed increased cases in Bancoumana, Mali [22], while Sissoko *et al*. reported elevated incidence in suburban areas along the Niger River [23]. Studies in the Malian Sahel (Sotuba and Dire) [6] and in the Peruvian Amazon in 2016 also showed that malaria cases peaked during the rainy season, with urban areas generally exhibiting lower incidence than rural areas. In our study, Sikasso—a more urbanized district—experienced relatively lower incidence, followed by Kati, which is less humid. While urbanization is often considered unfavorable for Anopheles proliferation, Sissoko *et al*. (2017) noted that increasing urbanization in Sotuba did not reduce malaria incidence [23].

Across all districts, children under five consistently had higher malaria incidence than individuals aged five and older between 2016 and 2018, highlighting the vulnerability of this age group [24]. This susceptibility is likely due to the underdeveloped immune system in young children and their higher rates of health facility attendance, partly because malaria treatment is provided free of charge for this age group. Peak incidence for both age groups occurred between July and October, with the highest peak observed in September 2016 among children under five. The lower peaks in 2017 and 2018 may reflect the door-to-door SMC delivery strategy introduced by the NMCP, which improved coverage

compared to the fixed-site strategy. Despite four SMC rounds, extreme incidence peaks were still observed, possibly because malaria cases are detected at the community level during SMC rather than at health facilities.

Notably, reductions in incidence among children under five were observed immediately following the third or fourth rounds of SMC, particularly from October to November, suggesting a beneficial impact of SMC on child health indicators, especially malaria incidence.

Maximum temperatures reached up to 40 °C in April, with a gradual increase in temperature from January to June. During this period, malaria incidence decreased in the general population, which may be explained by extreme temperatures (above 35 °C) reducing mosquito longevity as humidity decreases [25].

Correlation analyses between incidence and time (months) provided insight into the effects of control strategies, including SMC, on children under five. Kadiolo exhibited the largest reduction in malaria incidence (24.14%) between 2016 and 2018, whereas Yorosso showed a slight negative change.

Rainfall was highest between July and August over the three years, coinciding with the beginning of the SMC campaigns. Malaria incidence increased during this period, with the highest rates observed toward the end of the rainy season (September–October), reflecting the creation of mosquito breeding sites. The timing of SMC implementation consistently followed the onset of the high-transmission season across all districts. This delay may be influenced by funding availability and spatial heterogeneity in malaria transmission. Climatic variability can also shift the onset of the rainy season [26, 27], which should be further explored in future studies.

Overall, the percentage change in malaria incidence between 2016 and 2018 indicates reductions in some districts, likely due to control interventions and seasonal climatic factors. However, incidence increased in Sikasso and Yorosso, possibly due to extended and higher rainfall in 2018, which lasted until November [28, 29].

*Comparison of meteorological variables across health districts*

The average monthly relative humidity differed significantly among the five study districts over the three-year period (p < 0.001). In contrast, no significant differences were observed in the monthly mean temperature or average rainfall between the districts during the same period **(Table 3).**

**Table 3.** Comparative analysis of meteorological variables across the five health districts.

| Variable | p-Value | Statistical Test |
|---|---|---|
| Mean monthly rainfall | 0.296 | ANOVA |
| Mean monthly temperature | 0.686 | ANOVA |
| Mean monthly relative humidity | <0.001 | Kruskal–Wallis |

Univariate comparisons across the five health districts revealed that relative humidity varied significantly between sites (Kruskal–Wallis test, p < 0.001), whereas no notable differences were observed for mean monthly rainfall (ANOVA, p = 0.296) or temperature (ANOVA, p = 0.696) **(Table 3).**

These results indicate that relative humidity may have a stronger influence on malaria transmission than rainfall, corroborating findings from previous research [30, 31]. Differences in humidity between districts likely contribute to variations in transmission intensity. While heavy rainfall has been associated with higher malaria incidence in other studies [32], the effect of relative humidity reflects the indirect role of temperature and rainfall on mosquito survival, breeding success, longevity, and vectorial capacity.

Principal component analysis of the combined meteorological variables identified two main components. The first component (Dim-1) was primarily driven by relative humidity, with negative contributions from average and maximum temperatures, whereas the second component (Dim-2) included minimum temperature and rainfall. Dim-1 demonstrated a strong positive association with malaria incidence (p < 0.001), indicating its major role in disease dynamics. Dim-2 was also significantly associated with malaria incidence in the Sudano-Guinean zone (p < 0.05) **(Table 4).**

**Table 4.** Multivariate relationship between meteorological components and malaria incidence assessed using the Generalized Additive Model (GAM).

| Component | Zone | p-Value | Explained Deviance |
|---|---|---|---|
| Dim-2 | Sahel and Northern Sudan | <0.001 | 74% |
| Dim-1 | Sahel and Northern Sudan | <0.001 | — |
| Dim-2 | Sudano-Guinean | 0.006 | 50% |
| Dim-1 | Sudano-Guinean | <0.001 | — |

Malaria transmission is strongly influenced by a combination of meteorological factors, particularly rainfall, humidity, and temperature (both mean and minimum), as reported in several studies [23]. This relationship is often observed as a direct correlation without accounting for delays, though in other regions the lag between rainfall and malaria incidence can vary. Rainfall alone does not determine transmission; other elements, such as temperature, humidity, land cover, and land use, are also critical [18, 23, 24]. Because malaria dynamics differ based on local environmental and geographical conditions, variations in transmission between areas are expected.

Research consistently shows that rainfall and humidity enhance malaria risk by creating favorable habitats for mosquito breeding and increasing vector density [30, 33, 34]. Transmission can persist despite intensified control efforts, suggesting that interventions should consider climatic conditions and be adapted over time, with targets customized for different eco-climatic zones [3, 9, 35, 36]. In Mali, the start of the rainy season is characterized by decreasing temperatures, rising humidity, and increased vegetation, which contribute to the formation of larval breeding sites near homes [37-39]. Mosquitoes emerging from hibernation resume egg-laying [40], and under suitable environmental conditions, the breeding cycle can shorten from five weeks to as little as one week depending on the species. Vegetation provides protection for immature stages of mosquitoes, allowing their populations to grow rapidly [40]. Human carriers, including those without symptoms, maintain the reservoir necessary for ongoing transmission [41].

As the rainy season ends, rising temperatures reduce humidity and vegetation cover, prompting mosquitoes to migrate to more favorable humid microhabitats to survive [42, 43]. Climate, therefore, is a key driver of malaria transmission in Mali. This period represents a critical window for implementing interventions such as seasonal malaria chemoprevention (SMC), insecticide-treated nets, and indoor residual spraying. Control strategies, however, must be tailored to local conditions, as the timing and duration of the rainy season vary between locations.

**Conclusion**

The patterns of malaria transmission, including its seasonal fluctuations and variability, persist even in the presence of interventions like SMC and other control

measures. Nevertheless, malaria incidence declines following SMC cycles, with a noticeable reduction observed among children under five in 2017 and 2018 compared to 2016. The findings of this study indicate that meteorological factors play a significant role in influencing malaria incidence.

Furthermore, the study highlights that preventive measures such as SMC can be highly effective when implemented with carefully timed start periods tailored to each health district.

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