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Residual Malaria Burden and Strategic Targeting of Intermittent Preventive Treatment for Schoolchildren in Oyo State, Nigeria: An Integrated Geospatial Decision-Support Framework

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Abstract

School-aged children (5–15 years) represent an increasingly important but underprotected reservoir of malaria transmission in Nigeria, yet evidence for geographically prioritized intermittent preventive treatment for schoolchildren (IPTsc) remains limited. This study developed an integrated geospatial decision-support framework to quantify the residual malaria burden, identify persistent transmission reservoirs, and evaluate the operational feasibility of school-based IPTsc implementation in Oyo State, Nigeria. Multisource datasets comprising routine underfive malaria surveillance, Malaria Atlas Project (MAP) transmission products (2000–2024), WorldPop population data, GRID3 primary schools, health facilities, road networks, travel-time accessibility, and nighttime lights were harmonized within a geographic information system. Three complementary analytical components were developed: (i) a residual burden uncertainty index (RBUI) integrating underfive malaria burdens with persistent transmission; (ii) a transmission reservoir uncertainty index (TRUI) combining current transmission intensity with long-term persistence; and (iii) a school-level school-level opportunity index (SOI) and IPTsc priority index incorporating the school-age population, healthcare accessibility, and operational feasibility. The analysis revealed pronounced spatial heterogeneity in the residual malaria burden and transmission persistence across the state. The school-level assessment included 2,839 primary schools serving an estimated 2.66 million children aged 5–15 years during 2025, 40.0% of which were classified as high- or very high-priority for IPTsc implementation. The operational assessment indicated that 93.5% of the schools were suitable for health worker-supported delivery, whereas only 6.5% required teacher-supported administration following appropriate training because of reduced healthcare accessibility. The proposed framework integrates epidemiological risk with implementation readiness, providing a reproducible and scalable approach for evidence-based IPTsc prioritization. By *linking malaria burden, transmission persistence, school infrastructure, and delivery logistics, the framework offers practical decision support for geographically targeted malaria prevention and can be readily adapted to other malaria-endemic settings.*

Keywords: Malaria; IPTsc; school-aged children; geospatial analysis; malaria transmission; spatial epidemiology; school-based intervention; healthcare accessibility; Nigeria.

1. Introduction

Malaria remains one of the leading causes of morbidity and mortality in sub-Saharan Africa despite substantial progress in vector control, chemoprevention, rapid diagnosis, and effective case management over the past two decades [1,2]. Nigeria continues to account for the largest proportion of the global malaria burden, contributing to approximately one quarter of worldwide malaria cases and deaths, thereby representing the highest-priority country for malaria control and elimination efforts [1]. National malaria programs have achieved considerable reductions in malaria among children younger than five years through interventions such as insecticide-treated nets (ITNs), seasonal malaria chemoprevention (SMC), intermittent preventive treatment during pregnancy (IPTp), and improved access to diagnosis and treatment [2–4]. Nevertheless, malaria transmission persists across many endemic settings, suggesting that important reservoirs of infection remain insufficiently addressed by existing intervention strategies [5,6].

Increasing evidence indicates that school-aged children (5–15 years) constitute a substantial but frequently overlooked malaria reservoir [7–9]. Compared with younger children, school-aged children are less likely to receive preventive interventions but often harbor asymptomatic or low-density infections capable of sustaining community transmission [10,11]. Although this age group generally experiences lower malaria-related mortality than do children under five years of age do, their larger population size, frequent untreated infections, and continuous exposure to mosquito bites make them an important source of onward transmission [8,12]. Consequently, increasing attention has been given to intermittent preventive treatment for schoolchildren (IPTsc) as a complementary intervention capable of reducing malaria infection, improving school attendance, enhancing cognitive performance, and contributing to broader malaria control objectives [13–15].

Despite increasing interest in IPTsc, uncertainty remains regarding where implementation should be prioritized and whether a sufficient residual malaria burden exists outside populations already targeted by current interventions to justify additional investment [16,17]. Most malaria prioritization studies focus primarily on the current disease burden or parasite prevalence without explicitly evaluating the residual malaria burden after accounting for underfive interventions, long-term transmission persistence, or the operational feasibility of delivering IPTsc through existing school systems. As a result, programme managers frequently lack spatially explicit evidence identifying the geographic areas where IPTsc is likely to achieve the greatest epidemiological and operational benefit.

Recent advances in geographic information systems (GISs), remote sensing, and spatial epidemiology provide new opportunities to integrate routine health surveillance, malaria transmission products, demographic data, educational infrastructure, healthcare accessibility, and transportation networks within comprehensive geospatial decision-support frameworks. Such approaches enable simultaneous assessment of disease burden, transmission persistence, target populations, and implementation feasibility, thereby supporting evidence-based allocation of limited public health resources. However, relatively few studies have combined these complementary dimensions within a unified framework specifically designed to guide IPTsc implementation at both the school and district levels.

Another important limitation of previous studies is the predominant emphasis on epidemiological risk while giving comparatively little attention to operational delivery. Because IPTsc is implemented through schools rather than health facilities, programme success depends not only on identifying areas of high malaria burden but also on understanding school distribution, the school-age population, accessibility to supporting health facilities, transportation networks, and the most appropriate delivery mechanism for individual schools. Integrating epidemiological prioritization with operational planning therefore represents an important step toward translating malaria risk maps into implementable public health interventions.

This study addresses these knowledge gaps by developing an integrated geospatial framework to evaluate the potential role of school-aged children in sustaining malaria transmission and to identify priority areas for IPTsc implementation in Oyo State, Nigeria. Specifically, the study pursues three objectives: (i) to quantify residual malaria burden uncertainty by integrating underfive malaria burdens with persistent transmission indicators; (ii) to identify transmission reservoir uncertainty via long-term Malaria Atlas (MAP) transmission products; and (iii) to evaluate school-level IPTsc targeting and operational feasibility by integrating the school-age population, primary school distribution, healthcare accessibility, and transportation infrastructure. These complementary analyses are subsequently combined into a composite IPTsc priority index that supports evidence-based prioritization of primary schools and local government areas (LGAs) for phased programme implementation.

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2. Materials and methods

2.1 Study area

Oyo State is located in southwestern Nigeria between approximately 7°03′–9°12′ N and 2°47′–4°23′ E, covering an area of approximately 28,454 km². The state shares boundaries with Kwara State to the north, Osun State to the east, Ogun State to the south, and the Republic of Benin to the west. Administratively, Oyo State comprises 33 local government areas (LGAs), with Ibadan serving as the state capital and principal urban center.

The state exhibits marked environmental and demographic heterogeneity, encompassing densely populated metropolitan LGAs within the Ibadan urban agglomeration and predominantly rural agricultural landscapes across the northern and western regions. Population density, settlement patterns, transportation infrastructure, and access to healthcare services vary substantially among LGAs, resulting in spatial heterogeneity in healthcare accessibility and malaria intervention coverage.

Malaria remains endemic throughout Oyo State, with transmission occurring year-round and seasonal intensification during the rainy season. Although substantial reductions in malaria burden have been achieved through insecticide-treated nets (ITNs), seasonal malaria chemoprevention (SMC), improved case management, and other underfive interventions, persistent malaria transmission continues to be reported in several parts of the state. School-aged children (5–15 years), who are not routinely targeted by current preventive strategies, may therefore constitute an important residual parasite reservoir capable of sustaining community transmission.

The combination of heterogeneous malaria transmission, diverse settlement characteristics, extensive primary school infrastructure, and variable healthcare accessibility makes Oyo State an appropriate setting for evaluating residual malaria burden and assessing the operational feasibility of intermittent preventive treatment for schoolchildren (IPTsc) via an integrated geospatial framework.

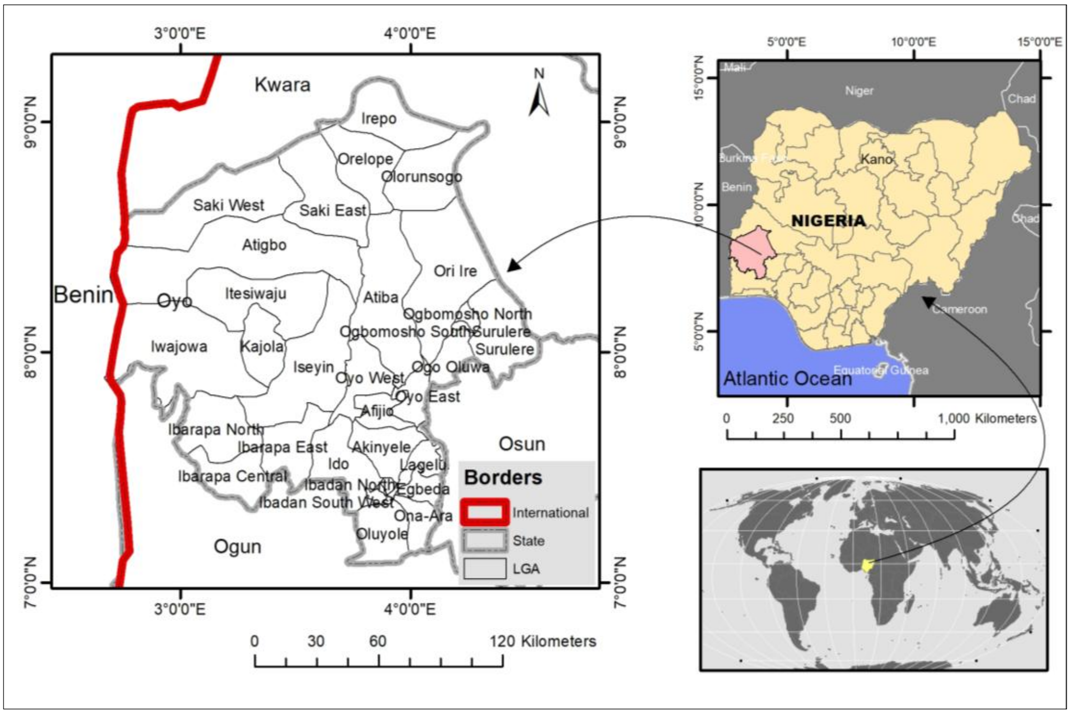

Figure 1. Location of Oyo State, Nigeria, showing the study area and the administrative boundaries of the 33 local government areas (LGAs) used for the geospatial analyses.

2.2 Research design and analytical workflow

Figure 2 summarizes the geospatial analytical framework developed to identify priority areas for intermittent preventive treatment for schoolchildren (IPTsc) in Oyo State, Nigeria. The workflow integrates routine underfive malaria surveillance, Malaria Atlas Project (MAP) transmission products, primary school locations, health facilities, road networks, travel-time accessibility, demographic data, and remotely sensed socioeconomic proxies within a harmonized geospatial database.

The analytical framework comprises three sequential components. Objective 1 quantifies residual malaria burden uncertainty by integrating the underfive malaria burden with persistent transmission indicators. Objective 2: To assess transmission reservoir uncertainty by combining current malaria transmission with long-term transmission persistence to identify areas where school-aged children may sustain malaria transmission. Objective 3 translates these epidemiological findings into an operational implementation framework by integrating the school-age population, primary school distribution, and healthcare accessibility to identify priority schools and delivery support models. The outputs from the three objectives are subsequently combined into a composite IPTsc priority index to support evidence-based prioritization of schools and LGAs for phased IPTsc implementation.

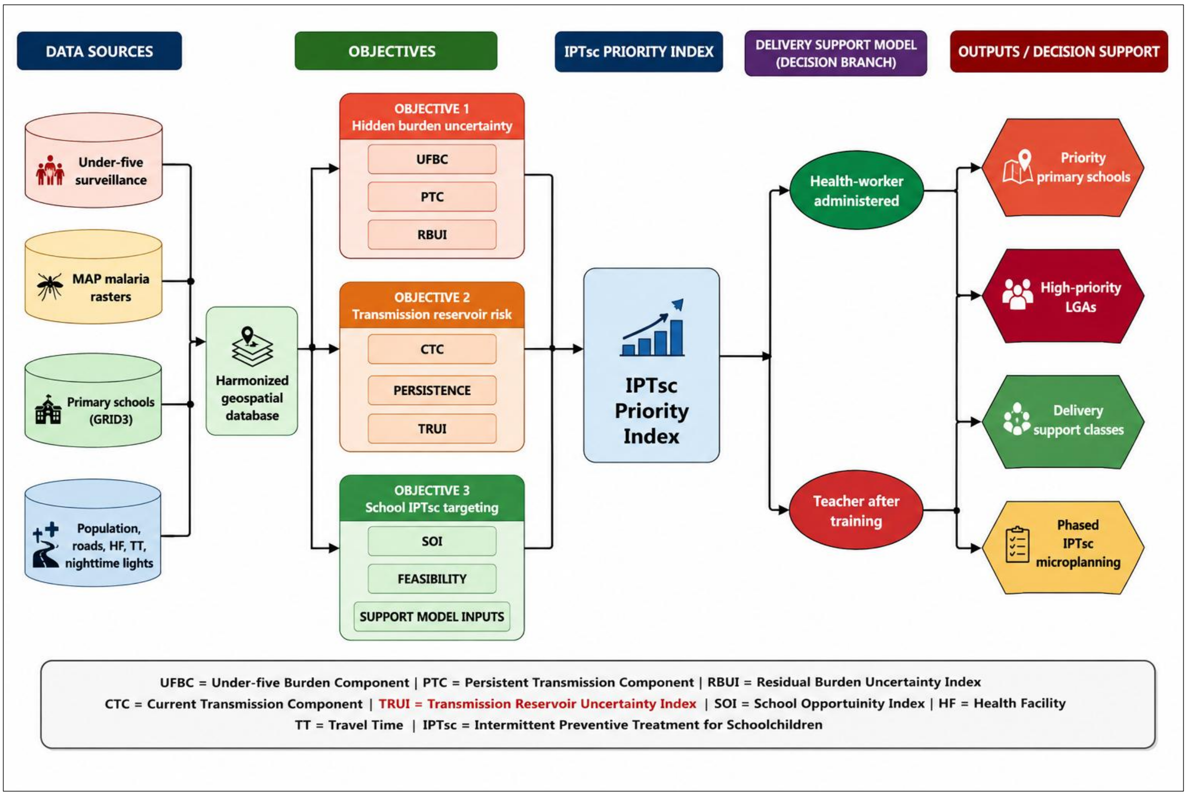

Figure 2. Conceptual framework illustrating the geospatial workflow for identifying priority areas for intermittent preventive treatment for schoolchildren (IPTsc) in Oyo State, Nigeria. The framework integrates three analytical components—residual malaria burden uncertainty, transmission reservoir uncertainty, and school-level IPTsc targeting—to derive a composite IPTsc priority index for evidence-based program planning and implementation.

2.2 Data used

The geospatial analysis integrated multiple datasets describing malaria epidemiology, population distribution, educational infrastructure, healthcare accessibility, transportation networks, and the environmental context. These datasets were obtained from national surveillance systems, global geospatial repositories, and remotely sensed products and were harmonized within a common spatial framework for subsequent analyses. Table 1 summarizes the datasets used in this study, including their data types, analytical purposes, and corresponding sources.

Table 1 Data Summary

Data	Data Type	Purpose	Source
Oyo State Boundary	Vector	Definition of study area and spatial clipping	OCHA Nigeria [18]
LGA Boundaries	Vector	Spatial aggregation, zonal statistics, and LGA-level analysis	OCHA Nigeria [18]
Underfive Malaria Surveillance (2025)	Vector (LGA)	Estimation of underfive malaria burden, severe malaria burden, malaria deaths, and SMC coverage for Residual Burden Uncertainty analysis	RHIS/DHIS2 [19]
Malaria Atlas Project (MAP) Products (2000–2024)	Annual Raster	Long-term malaria transmission dynamics (PfPR, PfIR, PfMR, PfMC, PfIC) and transmission persistence analysis	Malaria Atlas Project [20]

Primary Schools	Vector (Point)	Identification of IPTsc delivery sites and school-level operational assessment	GRID3 Nigeria School Database [21]
Health Facilities	Vector (Point)	Assessment of healthcare accessibility and delivery support capacity	National Health Facility Registry (NHFR) [22]
Road Network	Vector (Line)	Evaluation of transportation accessibility and operational connectivity	OpenStreetMap (OSM) [23]
Travel Time to Healthcare	Raster	Assessment of healthcare accessibility and classification of IPTsc delivery support models	Weiss et al. Global Motorized Travel Time Dataset [24]
Population 0 years (2025)	Raster (100 m)	Population reference layer	WorldPop [25]
Population 1 year (2025)	Raster (100 m)	Underone population used for estimation of residual malaria burden	WorldPop [25]
Population 5 years (2025)	Raster (100 m)	Derivation of school-age population	WorldPop [25]
Population 10 years (2025)	Raster (100 m)	Derivation of school-age population	WorldPop [25]
Population 15 years (2025)	Raster (100 m)	Estimation of school-age population (5–15 years) for IPTsc targeting	WorldPop [25]
Nighttime Lights (2025)	Raster	Proxy indicator of socioeconomic development and settlement intensity	NOAA VIIRS [26]

Abbreviations: IPTsc = Intermittent Preventive Treatment for Schoolchildren; SMC = Seasonal Malaria Chemoprevention; MAP = Malaria Atlas Project; PfPR = *Plasmodium falciparum* Parasite Rate; PfIR = *Plasmodium falciparum* Infection Rate; PfMR = *Plasmodium falciparum* Mortality Rate; PfMC = *Plasmodium falciparum* Malaria Cases; PfIC = *Plasmodium falciparum* Incidence Cases; RHIS = Routine Health Information System; DHIS2 = District Health Information System 2; GRID3 = Georeferenced Infrastructure and Demographic Data for Development; NHFR = National Health Facility Registry; OSM = OpenStreetMap; VIIRS = Visible Infrared Imaging Radiometer Suite; LGA = Local Government Area; HF = Health Facility.

2.4 Geospatial analytical framework

A hierarchical geospatial analytical framework was developed to quantify the residual malaria burden, identify persistent malaria transmission potentially maintained by school-aged children, and evaluate the operational feasibility of implementing intermittent preventive treatment for schoolchildren (IPTsc) across Oyo State, Nigeria (Figure 2). The framework integrates routine malaria surveillance, long-term malaria transmission products from the Malaria Atlas Project (MAP), demographic datasets, school infrastructure, health facilities, transportation networks, travel-time accessibility, and remotely sensed socioeconomic proxies within a geographic information system (GIS).

All spatial analyses were performed in R version 4.5 via the sf, terra, exactextractr, spdep, tidyverse, ggplot2, and tmap packages. All datasets were transformed into a common projected coordinate reference system and clipped to the Oyo State administrative boundary prior to analysis. Raster datasets were summarized at the local government area (LGA) level via area-weighted zonal statistics, whereas point datasets were spatially joined to administrative units via spatial intersection operations.

To permit the integration of variables measured in different units, continuous indicators were normalized to a common 0–1 scale via min–max standardization:

$$X_i^* = \frac{X_i - \min(X)}{\max(X) - \min(X)} \quad (1)$$

where X_i is the observed value for location i and where X_i^* is the standardized indicator.

2.4.1 Residual malaria burden uncertainty

The first objective quantified the malaria burden potentially remaining outside current under-five intervention strategies. Two complementary components were developed.

The **underfive burden component (UFBC)** summarizes routine surveillance indicators describing malaria morbidity, severe malaria, malaria-related mortality, and preventive intervention coverage among children younger than five years. A higher malaria burden increased the component score, whereas higher seasonal malaria chemoprevention (SMC) coverage reduced the score.

The component was calculated as

$$UFBC = \frac{M + SM + D + (1 - SMC)}{4} \quad (2)$$

where

M= standardized malaria incidence,

SM= standardized severe malaria burden,

D= standardized malaria mortality,

SMC= standardized seasonal malaria chemoprevention coverage.

The persistent transmission component (PTC) represents the environmental transmission intensity via four independent MAP indicators:

- Parasite prevalence (PfPR),
- Malaria incidence (PfMC),
- Infection rate (PfIR),
- Malaria mortality rate (PfMR).

The component was computed as

$$PTC = \frac{PfPR + PfMC + PfIR + PfMR}{4} \quad (3)$$

The two components were subsequently integrated to estimate the residual burden uncertainty index (RBUI):

$$RBUI = \frac{UFBC + PTC}{2} \quad (4)$$

Higher RBUI values indicate areas where routine underfive interventions coexist with substantial malaria transmission, suggesting that school-aged children may constitute an important untreated reservoir.

LGAs were classified into five implementation priority classes via quantile classification:

- Very low
- Low
- Moderate
- High
- Very High

The relationship between UFBC and PTC was further examined via Pearson correlation and scatterplot analysis.

2.4.2 Transmission reservoir uncertainty

The second objective investigated whether the declining malaria burden among children younger than five years coincided with persistent malaria transmission, indicating the possible contribution of school-aged children to ongoing malaria transmission.

Annual MAP rasters for
- PfPR,
- PfIR,
- PfMR,
- PfMC,
- PfIC

covering 2000–2024 were clipped to Oyo State and summarized to LGA-level annual means via exact area-weighted extraction.

For each indicator, three complementary metrics were calculated.

First, the **current transmission component** represents the 2024 transmission intensity.

Second, long-term changes between 2000 and 2024 were estimated as follows:

$$\Delta X = X_{2024} - X_{2000} \tag{5}$$

Third, the temporal trend for each LGA was quantified via Sen's slope estimator:

$$\beta = \text{Median}\left(\frac{X_j - X_i}{j - i}\right), j > i \tag{6}$$

where β represents the monotonic rate of change over time.

The persistence component was defined as

$$PTC = \frac{Current + (1 - | \, Trend \, |)}{2} \tag{7}$$

where persistent transmission receives higher scores when the current transmission remains elevated despite long-term reductions.

The **transmission reservoir uncertainty index (TRUI)** was then calculated as

$$TRUI = \frac{Current + Persistence}{2} \tag{8}$$

LGAs were subsequently classified into five transmission reservoir priority classes to identify areas where IPTsc may provide additional epidemiological benefit.

2.4.3 School-level IPTsc targeting and operational feasibility

The third objective translated epidemiological findings into an operational implementation framework by integrating the malaria burden with educational infrastructure.

Only schools classified as **primary** within the GRID3 national school database were retained because IPTsc is implemented through primary schools.

School catchments were generated via Thiessen (Voronoi) polygons constrained by the Oyo State boundary. The population aged 5–15 years was estimated by combining WorldPop age-specific population rasters:

$$Population_{5-15} = Population_{0-15} - Population_{0-5} \tag{9}$$

Each school catchment was assigned
- the school-age population,
- residual malaria burden,
- travel time to the nearest health facility,
- road accessibility,
- healthcare availability,
- nighttime light intensity.

The **School Opportunity Index (SOI)** was calculated as

$$SOI = \frac{Population + RBUI + Accessibility + Infrastructure + Socioeconomic}{5} \tag{10}$$

where all variables were standardized between 0 and 1.

The schools were subsequently classified into

- Very low,
- Low,
- Moderate,
- High,
- Very High

implementation opportunity classes.

2.4.4 School delivery support model

Unlike conventional malaria interventions, which are delivered directly through health facilities, IPTsc is administered within schools. Therefore, a delivery-support model was developed to determine the most appropriate operational strategy for each primary school.

The nearest health facility was identified via Euclidean nearest-neighbor analysis, whereas healthcare accessibility was quantified via the national motorized travel-time raster.

The schools were assigned to one of two operational delivery models:

Health worker-supported delivery

Schools located within acceptable travel-time thresholds from the nearest health facility were classified as suitable for routine visits by trained healthcare personnel responsible for drug administration, supervision, adverse event monitoring, and programme reporting.

Teacher-supported delivery

Schools located in geographically less accessible areas were classified as requiring teacher-supported IPTsc delivery. Under this model, teachers receive standardized training from the health sector and administer IPTsc under periodic supervision by healthcare personnel.

The delivery-support classification was determined as

$$Delivery = \begin{cases} Health\,Worker, & TT \le T_c \\ Teacher\,Support, & TT > T_c \end{cases} \tag{11}$$

where

- TT denotes the travel time to the nearest health facility,
- where T_c represents the operational accessibility threshold adopted by the program.

2.4.5 LGA prioritization

School-level indicators were aggregated to the LGA level to support district-level planning.

The **LGA IPTsc priority index (IPI)** combined

- average school opportunity,
- number of high-priority schools,
- the school-age population,
- operational feasibility,
- residual malaria burden.

The composite index was calculated as

$$IPI = \frac{SOI + Schools + Population + Feasibility + RBUI}{5} \tag{12}$$

LGAs were finally classified into five implementation priority classes via quantile classification to support phased program implementation and resource allocation.

3. Results

3.1 Hidden Burden Uncertainty and Residual Malaria Burden Patterns

Hidden burden uncertainty analysis revealed substantial spatial heterogeneity in the residual malaria burden across Oyo State. The mean residual burden uncertainty index (RBUI) across the 34 LGAs was 0.481, with values ranging from 0.130 to 0.768, indicating marked differences in the extent to which the malaria burden may persist beyond the reach of current underfive interventions. Overall, seven LGAs were classified as very high priority, whereas an additional seven LGAs were classified as high priority, suggesting that approximately 41% of LGAs present an elevated residual malaria burden that requires further programmatic attention.

The underfive burden component (UFBC) highlighted LGAs with high concentrations of reported underfive malaria cases, severe malaria cases, and malaria-related deaths relative to intervention coverage. The highest values were concentrated primarily within Surulere, Akinyele, Oluyole, Atiba, and Ibadan North, indicating areas where malaria morbidity remains substantial despite ongoing intervention efforts (Figure 3a). These LGAs reported some of the highest underfive malaria case burdens in the state, including 7,679 cases in Surulere, 6,892 cases in Akinyele, and 5,327 cases in Oluyole.

The persistent transmission component (PTC) showed a different but complementary spatial pattern, identifying LGAs where transmission indicators remained elevated despite underfive intervention efforts. High PTC values were observed in Akinyele (0.735), Surulere (0.697), and Oluyole (0.591), reflecting the continued presence of favorable transmission conditions and suggesting that current interventions may not fully suppress malaria transmission in these areas (Figure 3b).

The integration of UFBC and PTC into the residual burden uncertainty index revealed several LGAs where both burden and transmission remained simultaneously elevated (Figure 3c). The highest RBUI values were observed in Surulere (0.768), Akinyele (0.710), Ibadan North (0.659), Oluyole (0.626), and Atiba (0.614). These LGAs represent locations where the persistent malaria burden cannot be fully explained by current underfive intervention coverage alone and may therefore indicate an important contribution from underprotected populations, including school-aged children.

The RBUI priority classification further demonstrated a distinct geographic pattern (Figure 3d). Very high-priority LGAs were concentrated mainly within the central and southern portions of Oyo State, whereas moderate- and low-priority LGAs were more common in parts of the western and northern zones. The spatial distribution suggests that the residual malaria burden is not only associated with transmission intensity but also reflects differences in intervention effectiveness, healthcare access, and population vulnerability.

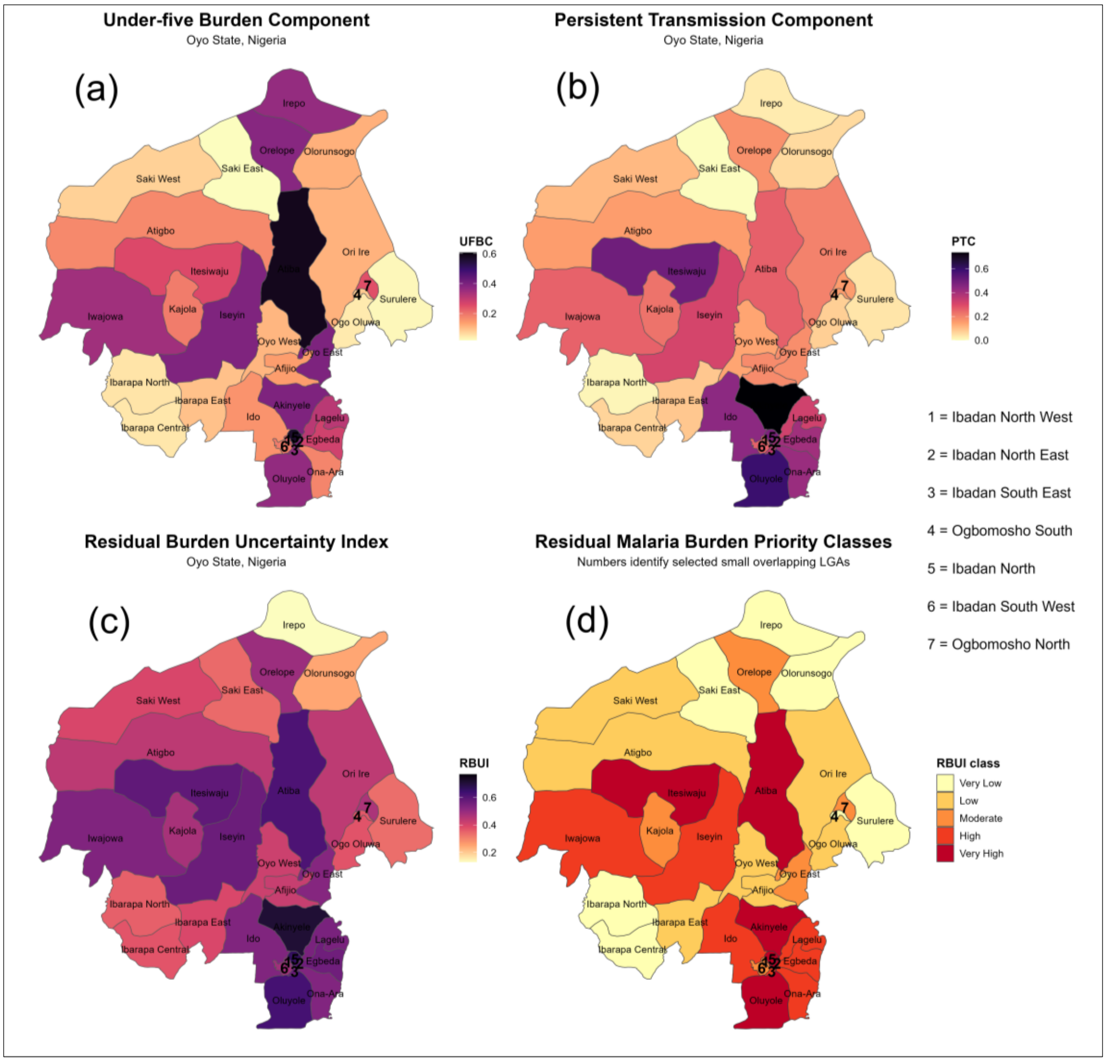

Figure 3. Components and spatial distribution of residual malaria burden uncertainty in Oyo State. (a) Underfive burden component (UFBC) derived from underfive malaria cases, severe malaria cases, malaria-related deaths, and intervention coverage; (b) persistent transmission component (PTC) derived from malaria transmission indicators; (c) residual burden uncertainty index (RBUI) integrating UFBC and PTC; and (d) residual malaria burden priority classes identifying LGAs with varying levels of residual malaria burden uncertainty.

The relationship between UFBC and PTC was further examined via scatterplot analysis (Figure 4). A positive association was observed between the two components, indicating that LGAs experiencing high underfive malaria burdens often also exhibited persistent transmission conditions. However, several LGAs deviated from this general trend, suggesting that residual burden may arise through different epidemiological pathways. For example, some LGAs exhibited high transmission persistence despite relatively lower underfive burdens, whereas others showed substantial underfive burdens despite only moderate transmission persistence. These deviations highlight the importance of considering both disease burden and transmission dynamics when identifying areas where school-aged children may represent a substantial residual malaria reservoir.

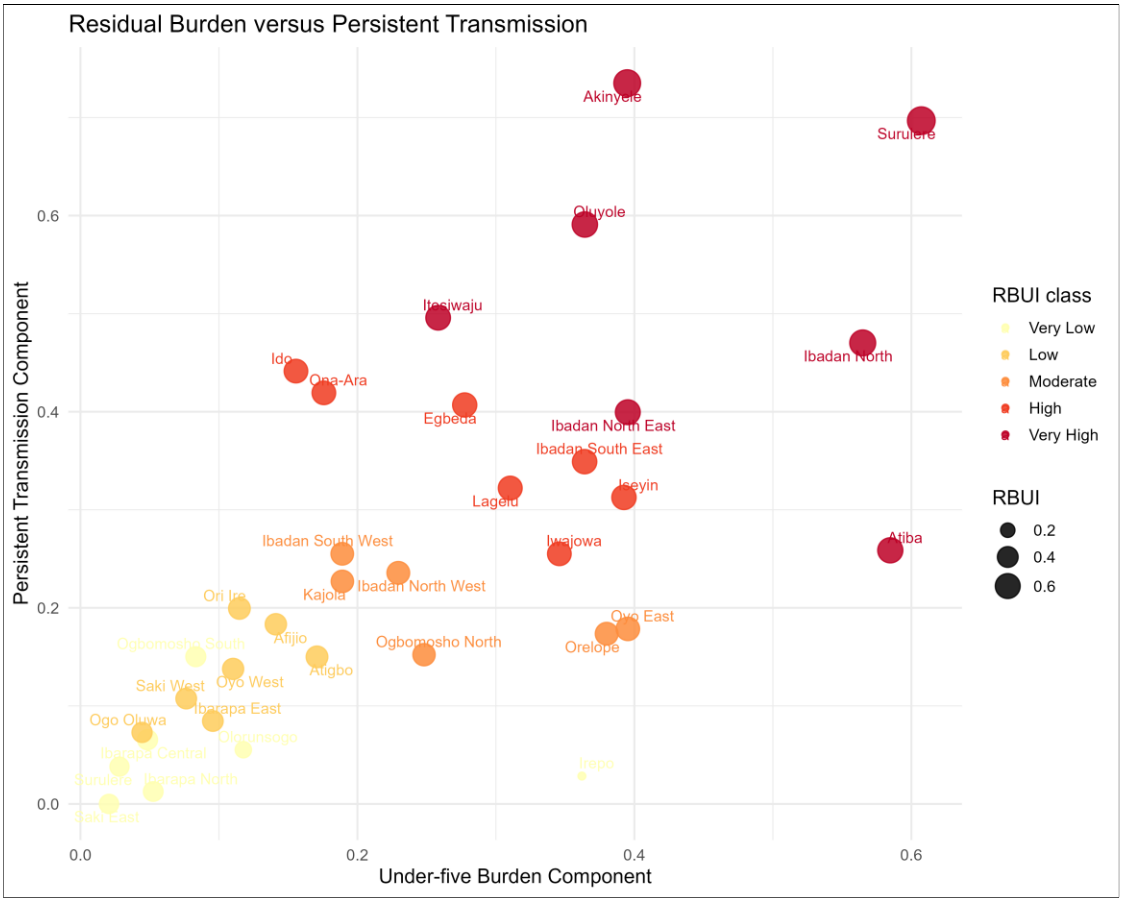

Figure 4. Relationship between the underfive burden component (UFBC) and persistent transmission component (PTC) across LGAs in the Oyo State.

Each point represents an LGA. The scatterplot illustrates the degree to which the residual malaria burden is jointly influenced by the underfive malaria burden and persistent transmission conditions. LGAs located in the upper-right quadrant simultaneously present high burdens and transmission persistence and therefore represent priority areas for further investigation of school-aged malaria burdens and potential IPTs.

Local Moran's I analysis revealed significant spatial clustering of the residual malaria burden. Lagelu emerged as the only statistically significant high-high hotspot (Local Z = 2.47, p = 0.013), indicating a concentration of elevated residual burden within a broader area of similarly high values. In contrast, Orelope was identified as a significant high–low spatial outlier (Local Z = −2.37, p = 0.018), suggesting localized residual burden patterns that differ from those of surrounding LGAs. These findings reinforce the presence of spatially structured uncertainty in malaria burden distributions and provide additional evidence for geographically targeted intervention strategies.

3.2 Transmission Reservoir uncertainty and persistent malaria transmission patterns

Long-term analysis of Malaria Atlas Project (MAP) indicators revealed substantial reductions in malaria transmission across Oyo State between 2000 and 2024, although considerable spatial heterogeneity remained. The state-level mean values of all five malaria indicators (PfPR, PfIR, PfMR, PfMC, and PfIC) exhibited declining trends during the study period (Figure 5). The mean parasite incidence (PfPR) declined from approximately 0.59 in 2000 to 0.28 in 2024, representing a reduction of more than 50%. Similarly, PfIR decreased from approximately 0.48 to 0.28, whereas PfMC decreased from approximately 38.5 to 13.5 cases. Malaria mortality (PfMR) also declined steadily from approximately 0.0018 to 0.0011. Although these results indicate substantial progress in malaria control over the last two decades, the persistence of nonzero transmission levels across all indicators suggests continued opportunities for malaria transmission within the state.

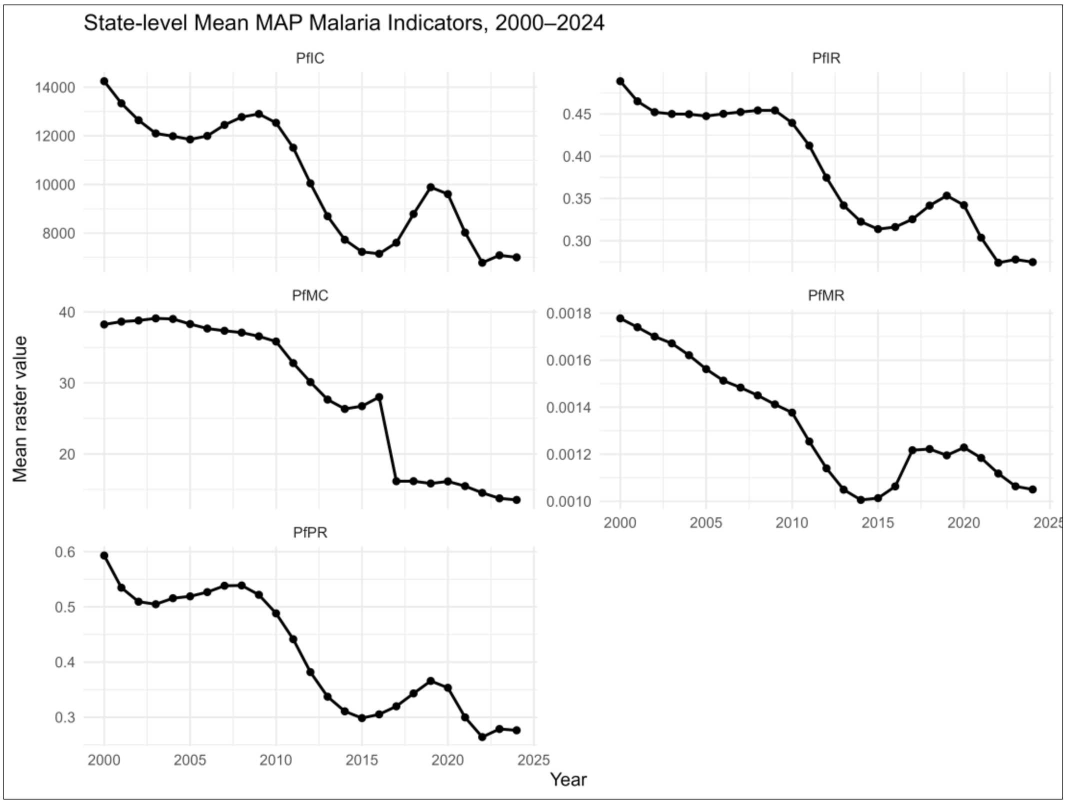

Figure 5. State-level temporal trends in Malaria Atlas Project indicators across Oyo State, 2000–2024. Annual state-wide mean values of parasite incidence (PfPR), parasite incidence rate (PfIR), malaria mortality rate (PfMR), malaria case incidence (PfMC), and parasite infection count (PfIC) derived from MAP raster datasets. All indicators show substantial long-term declines, although persistent transmission remains evident.

The Current Transmission Component (CTC) identified LGAs where malaria transmission remained relatively elevated in 2024 (Figure 6a). High CTC values were concentrated primarily within the northern and northwestern portions of Oyo State, particularly around Orelope, Saki East, Olorunsogo, Atigbo, Irepo, and Saki West. In contrast, lower values were observed within the Ibadan metropolitan region and several southern LGAs, indicating comparatively lower contemporary transmission intensity.

The persistence trend component (PTC) highlighted areas where malaria indicators showed slower rates of decline over the 2000–2024 period (Figure 6b). Elevated persistence values were concentrated in Orelope, Surulere, Olorunsogo, Saki East, and Atiba, indicating that malaria transmission remained relatively resilient despite overall state-wide reductions. Conversely, many southern and peri-urban LGAs presented lower persistence values, suggesting more substantial long-term improvements in malaria control outcomes.

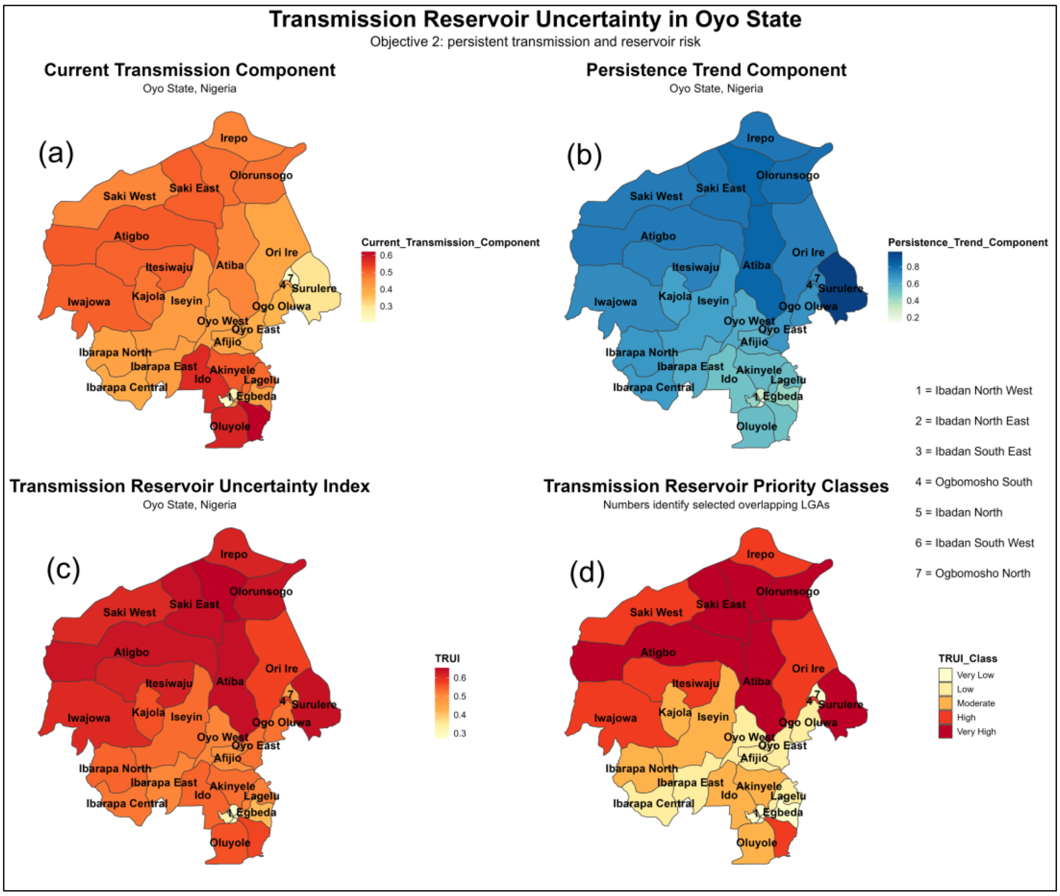

Figure 6. Spatial distribution of transmission reservoir uncertainty across Oyo State.
(a) Current transmission component representing contemporary malaria transmission intensity in 2024; (b) persistence trend component representing long-term resistance to transmission decline from 2000–2024; (c) transmission reservoir uncertainty index (TRUI) integrating current transmission and persistence metrics; and (d) TRUI priority classes identifying LGAs with differing levels of transmission reservoir uncertainty.

Combining contemporary transmission intensity with long-term persistence produced the transmission reservoir uncertainty index (TRUI), which represents the likelihood that school-aged children may contribute to continued malaria transmission despite existing interventions (Figure 6c). Across the 34 LGAs, the mean TRUI was 0.525, with values ranging from 0.272--0.653. Seven LGAs were classified as very high priority, and an additional seven LGAs were classified as high priority, indicating that approximately 41% of the LGAs exhibited elevated transmission reservoir uncertainty.

The highest TRUI values were observed in Orelope (0.653), Atiba (0.641), Saki East (0.641), Surulere (0.639), Olorunsogo (0.636), and Atigbo (0.634) (Figure 7). These LGAs consistently ranked highly in both current transmission intensity and persistence metrics, suggesting that malaria transmission remains entrenched despite long-term control efforts. Additional high-priority LGAs included Itesiwaju, Irepo, Saki West, Iwajowa, Ogbomosho South, Ori Ire, and Ona-Ara.

The TRUI priority classification revealed a clear geographic pattern (Figure 6d). Very high- and high-priority LGAs were concentrated predominantly within northern and northwestern Oyo State, whereas very low- and low-priority LGAs were largely associated with the Ibadan metropolitan region and adjacent southern LGAs. This pattern suggests that malaria transmission reservoirs may increasingly be concentrated within rural and perirural areas where intervention effectiveness remains comparatively limited.

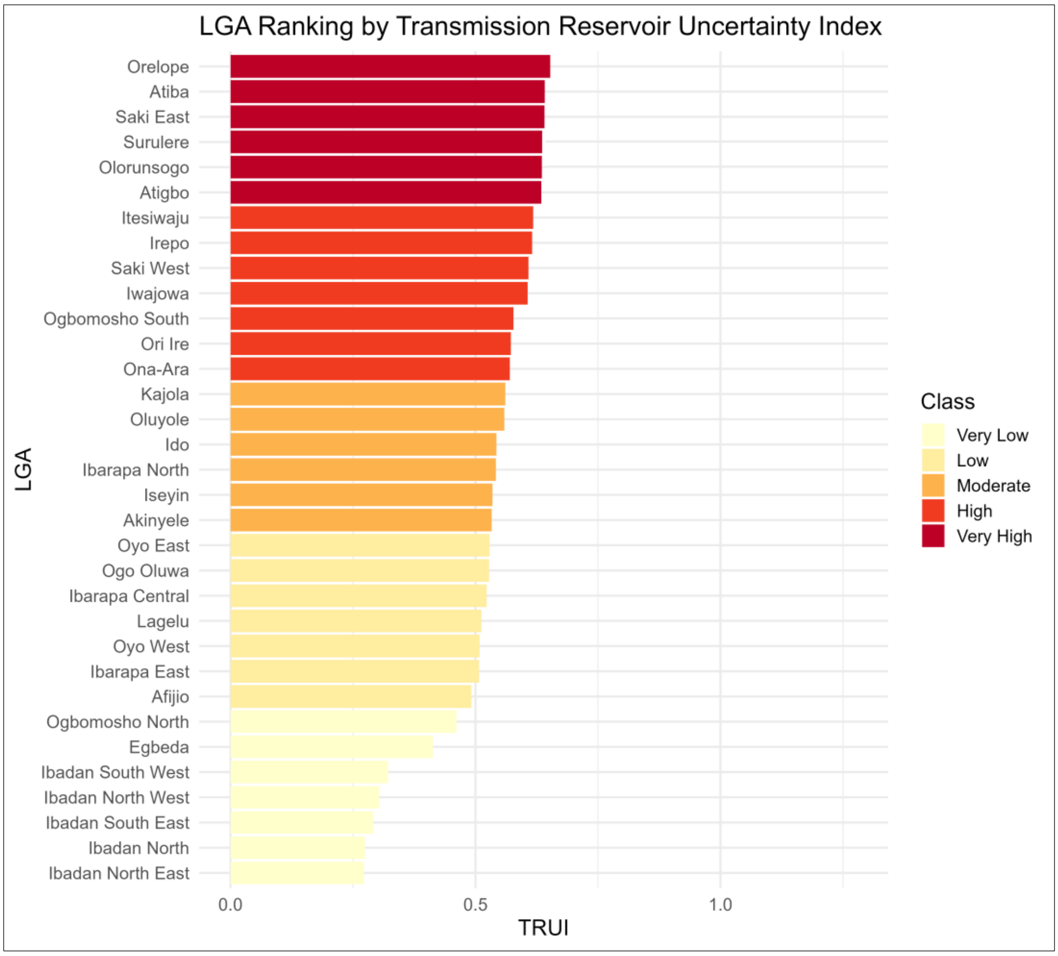

Figure 7. LGA ranking on the basis of the transmission reservoir uncertainty index (TRUI). LGAs are ranked according to their integrated transmission reservoir uncertainty score. Higher values indicate a greater likelihood that persistent malaria transmission remains sustained despite long-term reductions in the malaria burden and therefore represent priority areas for IPTsc targeting.

Spatial autocorrelation analysis further confirmed the existence of geographically structured transmission reservoirs. Local Moran's I identified three significant high–high hotspots representing clusters of elevated transmission reservoir uncertainty. In contrast, six significant low–low cold spots were identified, including Ibadan North West, Ibadan North East, and Ibadan South East, indicating areas where both local and neighboring LGAs exhibited consistently low transmission reservoir uncertainty. Two significant high–low outliers were also detected, suggesting localized transmission conditions that differ from those in surrounding areas. These findings demonstrate that persistent malaria transmission in Oyo State is spatially clustered rather than randomly distributed and provide strong evidence for geographically targeted IPTsc interventions.

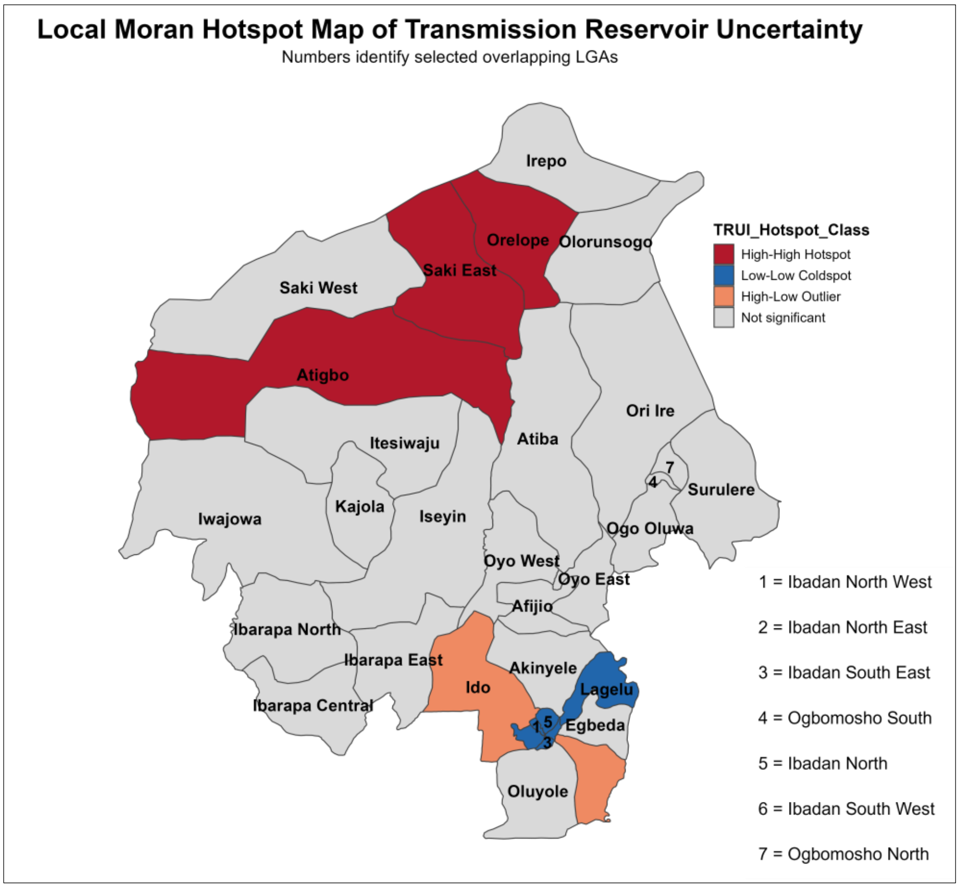

Figure 8. Local Moran's I hotspot analysis of transmission reservoir uncertainty.
High–high hotspots identify LGAs with elevated transmission reservoir uncertainty surrounded by similarly high-risk neighbors, whereas low–low coldspots indicate clusters of consistently low transmission reservoir uncertainty. High–low outliers represent localized areas of elevated transmission uncertainty within lower-risk neighborhoods.

Overall, Objective 2 demonstrates that although malaria transmission has declined substantially across Oyo State during the last two decades, several LGAs continue to exhibit persistent transmission conditions. These areas represent potential malaria transmission reservoirs and therefore constitute priority locations for further investigation and implementation of school-based malaria interventions.

3.3. Targeting and Operational Feasibility of School-Based IPTsc Delivery

3.3.1. Primary-school IPTsc opportunity

A total of **2,839 primary schools** were identified across Oyo State and included in the IPTsc targeting analysis after filtering the GRID3 school database to retain only schools classified under the **primary** category. The estimated school catchments represented approximately **2.66 million children aged 5–15 years**, providing a comprehensive spatial representation of the potential IPTsc target population.

The School Opportunity Index integrates the school-age population, residual malaria transmission risk, operational feasibility, healthcare support, and educational readiness to identify schools with the greatest strategic importance for IPTsc implementation. The mean school opportunity index across all schools was **58.96**, indicating moderate-to-high implementation potential statewide. Approximately **1,136 primary schools** (40.0% of all schools) were classified as **high** or **very high** priority for IPTsc implementation, demonstrating that malaria risk and operational opportunity are concentrated within a subset of schools rather than being uniformly distributed across the state.

Figure 9 illustrates the spatial distribution of the School Opportunity Index. High-priority schools were concentrated within LGAs exhibiting both elevated residual malaria transmission and relatively large school-age populations, whereas schools with lower opportunity scores generally occurred in areas with smaller target populations or comparatively lower transmission intensities.

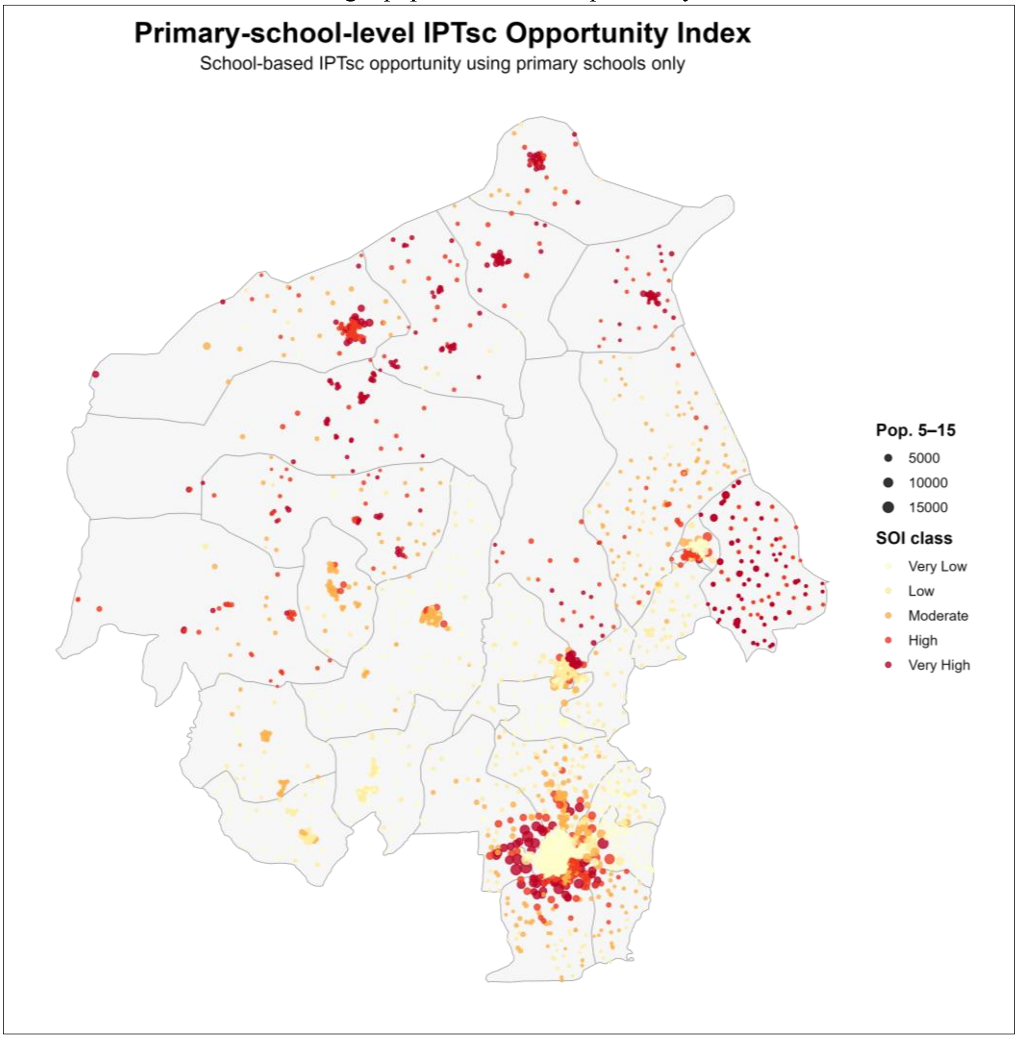

Figure 9. Spatial distribution of the primary school opportunity index across Oyo State. The composite index integrates the school-age population (5–15 years), residual malaria transmission risk, healthcare support, operational feasibility, and educational readiness to identify priority schools for school-based IPTsc implementation.

3.3.2. School-based delivery support model

To improve operational planning, each primary school was further classified according to the most appropriate delivery support model for IPTsc implementation. Unlike conventional facility-based health interventions, IPTsc is implemented within schools; therefore, the analysis distinguished schools according to the level of health system support required rather than the delivery platform itself.

Two implementation models were identified:

- **Health worker-administered school delivery**, where healthcare personnel can feasibly visit schools to supervise and administer antimalarial treatment; and
- **Teacher-administered school delivery after training**, where geographic accessibility limits routine health-worker visits, and trained teachers represent a more practical implementation strategy under health-sector supervision.

The results indicate that 2,655 schools (93.5%) were suitable for direct health worker-supported delivery, whereas only 184 schools (6.5%) required teacher-led administration following appropriate training and supervision (Figure 10). These teacher-supported schools are generally characterized by greater travel time to supervise health facilities, lower road accessibility, and relatively poorer operational connectivity. Consequently, although most schools could be integrated within existing primary healthcare outreach systems, a small but operationally important group of schools would benefit from strengthened teacher training, drug supply mechanisms, and supervisory support to ensure equitable IPTsc coverage.

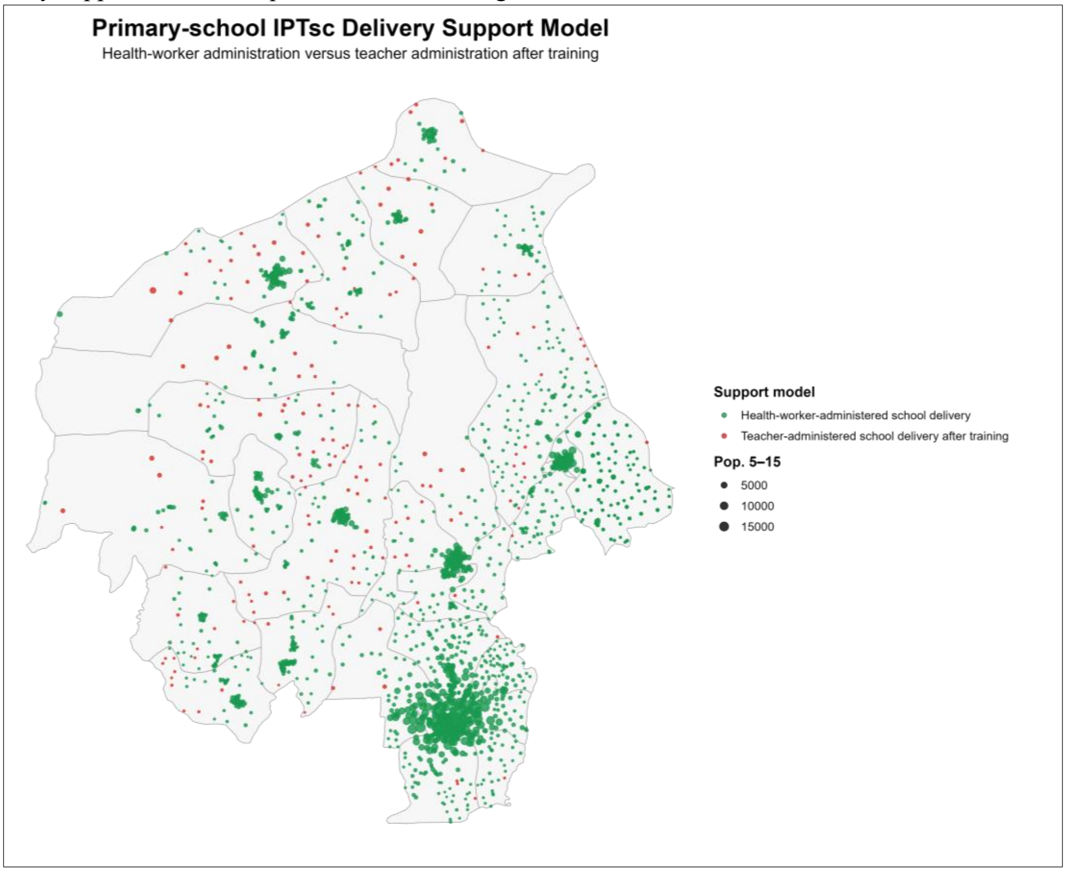

Figure 10. Spatial distribution of the primary school delivery support model. Schools were classified into (i) health worker-administered school delivery, where routine supervision and drug administration by healthcare personnel are operationally feasible, and (ii) teacher-administered school delivery after training, where geographical accessibility constraints favor teacher-led administration under health sector supervision.

The high mean operational feasibility index (**96.54**) further suggests that the existing educational and healthcare infrastructure in Oyo State provides favorable conditions for the large-scale implementation of school-based IPTsc.

3.3.3. LGA-level IPTsc targeting

The school-level indicators were subsequently aggregated to the local government area (LGA) level to identify geographic priorities for program implementation. Four complementary indicators were produced, including the composite LGA IPTsc Priority Index, categorical implementation priority, the number of high-priority primary schools, and the estimated school-age population (5–15 years) potentially served by primary schools (Figure 11).

The LGA IPTsc Priority Index combines malaria transmission intensity, aggregated school opportunities, the school-age population, school density, and operational feasibility into a single planning metric. Higher priority scores generally occurred in LGAs containing larger concentrations of high-opportunity schools together with substantial school-age populations, whereas lower-ranking LGAs typically presented fewer priority schools and comparatively smaller target populations.

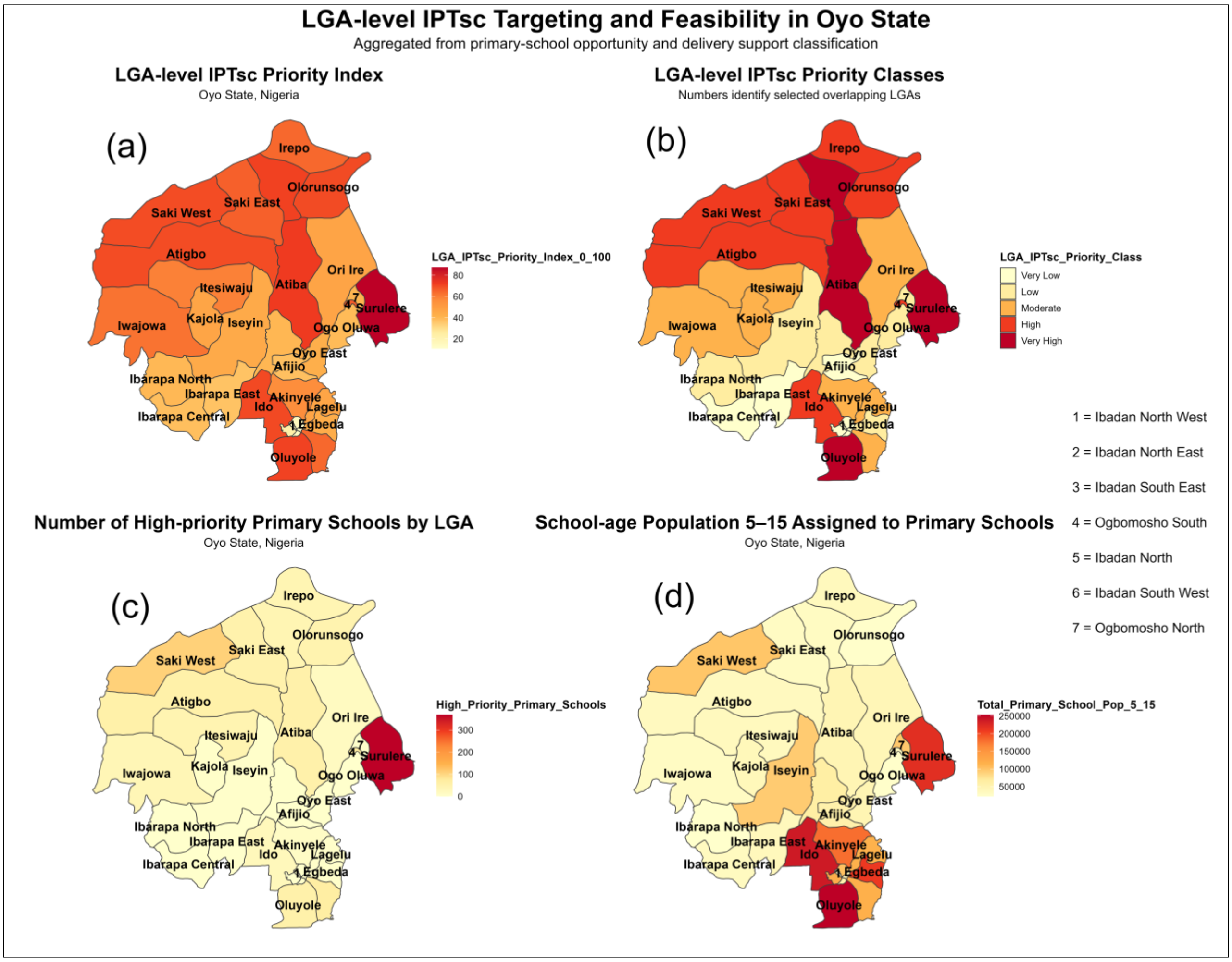

Figure 11. LGA-level prioritization for school-based IPTsc implementation in Oyo State: (a) composite LGA IPTsc priority index; (b) LGA IPTsc priority classes; (c) number of high-priority primary schools per LGA; and (d) estimated school-age population (5–15 years) associated with primary schools. The four panels collectively illustrate the spatial distribution of epidemiological needs, implementation opportunities, and operational targeting.

The distribution of high-priority schools closely followed the spatial pattern of the composite IPTsc priority index, indicating that priority LGAs are driven primarily by the accumulation of multiple strategically important schools rather than isolated high-risk locations. Similarly, the spatial distribution of the school-age population demonstrated that implementation needs are concentrated within relatively few LGAs, highlighting the importance of geographically targeted deployment strategies for maximizing programme efficiency.

Overall, the LGA analysis demonstrates that combining the epidemiological burden with school infrastructure and operational accessibility provides a practical framework for prioritizing IPTsc implementation across Oyo State.

3.3.4. LGA priority ranking

The ranked distribution of LGAs (Figure 12) illustrates substantial heterogeneity in IPTsc implementation priority across Oyo State. The highest-ranked LGAs simultaneously exhibited large school-age populations, numerous high-priority schools, favorable operational feasibility, and elevated residual malaria transmission, whereas lower-ranked LGAs generally combined smaller target populations with fewer priority schools and reduced epidemiological importance.

The ranking therefore provides a practical decision-support tool for phased implementation, enabling malaria control programmes to prioritize LGAs where school-based IPTsc is expected to achieve the greatest public health impact while making efficient use of available operational resources.

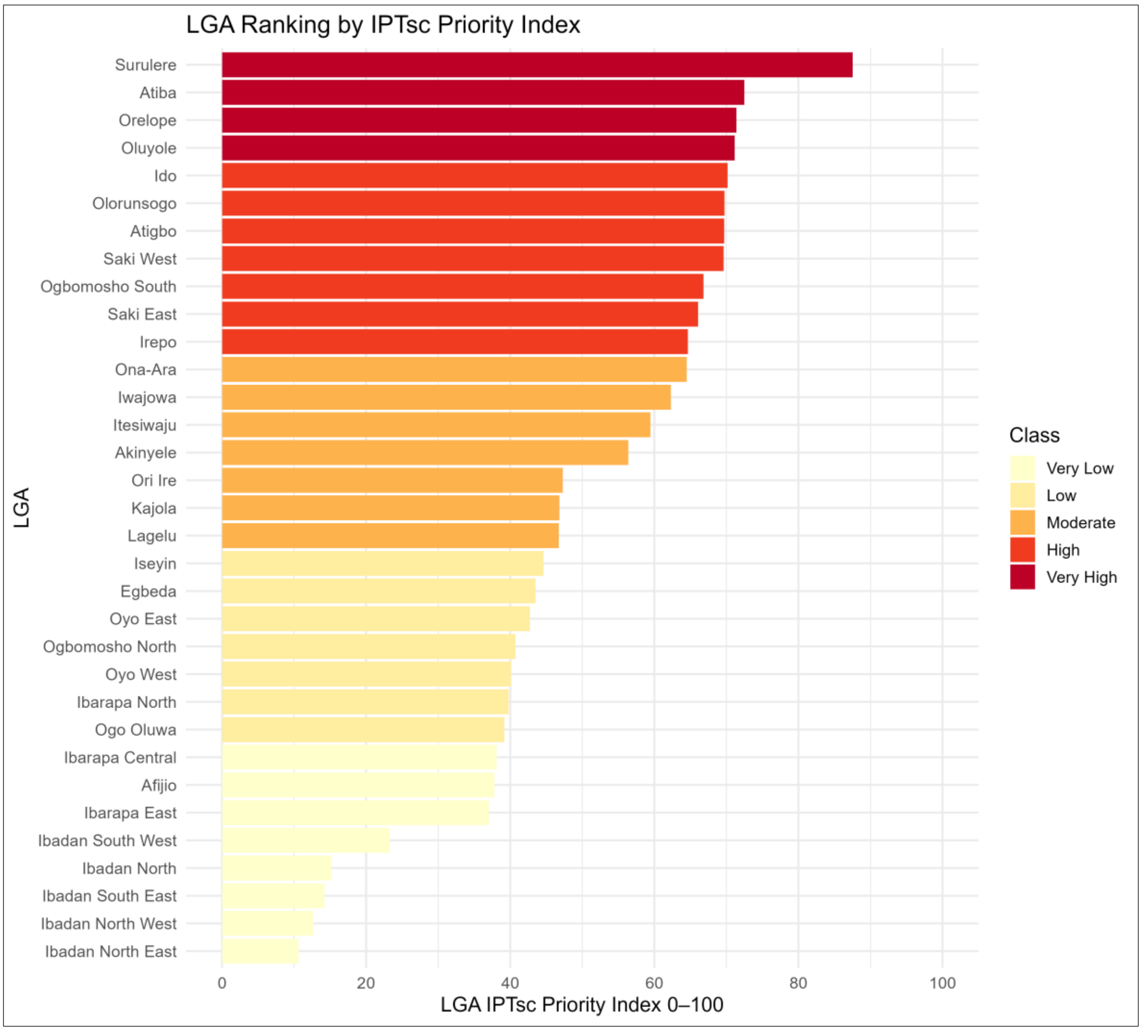

Figure 12. Ranking of local government areas according to the composite IPTsc priority index. Higher-ranked LGAs represent areas where favorable operational feasibility coincides with larger school-age populations, greater concentrations of high-priority schools, and elevated residual malaria transmission, indicating greater potential benefits from school-based IPTsc implementation.

4. Discussion

4.1. Residual malaria burden beyond current underfive interventions

Despite substantial investments in malaria control among children younger than five years, our findings demonstrate that considerable spatial heterogeneity in the residual malaria burden persists across Oyo State. LGAs exhibiting high residual burden uncertainty index (RBUI) values were characterized by the coexistence of substantial routine malaria burden and persistent transmission intensity, suggesting that current intervention packages alone may be insufficient to interrupt malaria transmission completely. These findings support increasing evidence that malaria programmes focused predominantly on children under five years leave an important epidemiological gap among school-aged children, who frequently remain outside routine preventive interventions while continuing to contribute to parasite transmission [27–30].

Previous studies have shown that although insecticide-treated nets, seasonal malaria chemoprevention, and improved case management substantially reduce severe disease and mortality among younger children, they do not eliminate community transmission because asymptomatic infections persist in older age groups [31,32]. Our geospatial framework extends these observations by identifying where this residual burden is geographically concentrated, thereby providing actionable information for prioritizing complementary interventions such as IPTsc.

Unlike previous studies that primarily mapped malaria incidence or parasite prevalence independently, the present study combines routine surveillance indicators with persistent transmission metrics within a unified spatial framework. This integrated approach provides a more comprehensive representation of residual malaria burden and better reflects programmatic uncertainty regarding populations that remain insufficiently protected.

4.2. School-aged children as potential transmission reservoirs

The second objective investigated whether school-aged children constitute an underrecognized malaria transmission reservoir. Although several LGAs demonstrated declining long-term malaria trends, relatively high current transmission rates persisted, resulting in elevated transmission reservoir uncertainty index (TRUI) values. This pattern indicates that reductions in malaria incidence have not been accompanied by proportional reductions in transmission potential, suggesting that untreated infections among school-aged children may continue to sustain malaria circulation.

These findings are consistent with numerous epidemiological studies reporting that school-aged children frequently harbor asymptomatic and submicroscopic infections while experiencing lower treatment-seeking behavior than younger children do [33–36]. Consequently, this population may maintain parasite circulation despite substantial progress in reducing clinical malaria among children under five years of age.

The observed spatial variation in transmission persistence further emphasizes that malaria elimination strategies should move beyond uniform intervention coverage and instead adopt geographically targeted approaches. Integrating long-term transmission dynamics with contemporary surveillance provides a more realistic assessment of future malaria risk than relying solely on current prevalence estimates does, thereby supporting evidence-based prioritization of IPTsc.

4.3. Operational feasibility of school-based IPTsc implementation

One of the principal contributions of this study is the integration of epidemiological prioritization with operational feasibility. Rather than focusing exclusively on malaria risk, the proposed framework incorporates school distribution, the school-age population, healthcare accessibility, transportation infrastructure, and delivery logistics to evaluate where IPTsc can be implemented most effectively.

The analysis demonstrated that most primary schools were suitable for routine health worker-supported delivery, whereas a relatively small proportion required teacher-supported administration following appropriate training and supervision. This distinction is particularly important because IPTsc is fundamentally a school-based intervention rather than a health facility intervention. Identifying schools requiring alternative delivery mechanisms enables programme managers to allocate supervisory resources more efficiently while maintaining equitable access for geographically isolated populations.

Previous IPTsc implementation studies have demonstrated the feasibility of teacher-assisted delivery under appropriate clinical supervision [37–39]. Our findings complement these studies by providing a spatially explicit framework capable of identifying where each delivery model is most appropriate. Such evidence can substantially improve operational planning, drug distribution, workforce allocation, and monitoring activities before program implementation.

4.4. Implications for malaria programme prioritization

The integrated IPTsc Priority Index developed in this study provides a practical decision-support tool for phased implementation of malaria prevention programs. Conventional prioritization strategies frequently rely on a single indicator, such as parasite prevalence or reported malaria incidence, potentially overlooking important operational constraints. In contrast, the present framework combines the epidemiological burden, transmission persistence, school-age population, healthcare accessibility, educational infrastructure, and transportation connectivity into a unified prioritization scheme.

This multicriteria approach enables malaria programs to distinguish between areas where IPTsc is both epidemiologically justified and operationally feasible. Consequently, limited financial and human resources can be directed toward LGAs, and schools are expected to yield the greatest public health benefits. This geographically targeted implementation aligns with current recommendations advocating precision public health approaches that maximize intervention efficiency through spatial prioritization [40–42].

Beyond IPTsc, the proposed methodology has broader applicability for planning school-based public health programs, including deworming, nutritional supplementation, vaccination campaigns, and health education initiatives, particularly in resource-constrained settings.

4.5. Strengths, limitations, and future research

This study has several strengths. First, it integrates multiple independent datasets describing malaria epidemiology, demographic distribution, educational infrastructure, healthcare accessibility, transportation networks, and remotely sensed socioeconomic conditions within a unified geospatial framework. Second, the analytical workflow combines epidemiological uncertainty with operational feasibility, thereby bridging the gap between malaria risk assessment and program implementation. Third, the methodology is reproducible and transferable to other malaria-endemic regions where routine surveillance and geospatial datasets are available.

Several limitations should also be acknowledged. Routine surveillance data may be affected by underreporting, reporting delays, and spatial variation in healthcare utilization. The school catchment model assumes proximity-based attendance and does not account for individual school choice or cross-boundary enrollment. Similarly, travel-time estimates represent modeled accessibility rather than observed travel behavior and may not fully capture seasonal road conditions or transportation availability. Finally, the IPTsc Priority Index represents a decision-support framework rather than a direct measure of program effectiveness and therefore requires validation through operational implementation studies.

Future research should integrate entomological surveillance, parasite genomic data, human mobility patterns, school attendance records, and cost-effectiveness analyses to further refine IPTsc prioritization. Prospective implementation studies evaluating the impact of the proposed framework on malaria incidence, programme efficiency, and economic outcomes would provide valuable evidence for scaling school-based malaria prevention strategies throughout Nigeria and other malaria-endemic countries.

Data availability statement:

Administrative boundary datasets for Oyo State and its Local Government Areas (LGAs) were obtained from the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) Common Operational Datasets for Nigeria and are publicly available at https://data.humdata.org/dataset/cod-ab-nga.

Under-five malaria surveillance data for 2025, including malaria cases, severe malaria cases, malaria deaths, and seasonal malaria chemoprevention (SMC) coverage indicators, were obtained from the Nigerian Routine Health Information System (RHIS) through the District Health Information System 2 (DHIS2) platform managed by the Federal Ministry of Health. These datasets are not publicly available due to national health data

governance and confidentiality requirements but may be made available from the relevant authorities subject to approval.

Annual malaria transmission products for the period 2000–2024, including *Plasmodium falciparum* Parasite Rate (PfPR), Infection Rate (PfIR), Mortality Rate (PfMR), Malaria Cases (PfMC), and Clinical Incidence (PfIC), were obtained from the Malaria Atlas Project and are publicly available at https://malariaatlas.org/explorer/.

Primary school locations used for identifying intermittent preventive treatment in schoolchildren (IPTsc) delivery sites were obtained from the GRID3 Nigeria School Database, available through the GRID3 data portal at https://data.grid3.org/.

Health facility locations and facility characteristics were obtained from the Nigerian National Health Facility Registry (NHFR) and are publicly available at https://hfr.health.gov.ng/.

Road network data used for transportation accessibility analyses were obtained from OpenStreetMap and are publicly available at https://www.openstreetmap.org/ and through regional extracts available at https://download.geofabrik.de/africa/nigeria.html.

Global travel time to healthcare data were obtained from the global motorized travel time dataset developed by Weiss et al. and are publicly available through the Malaria Atlas Project data repository at https://malariaatlas.org/research-project/accessibility-to-cities-and-healthcare-facilities/.

Age-specific population estimates for 2025, including populations aged 0, 1, 5, 10, and 15 years, were obtained from the WorldPop project and are publicly available at https://www.worldpop.org/ and through the WorldPop Open Population Repository at https://wopr.worldpop.org/.

Nighttime light intensity data for 2025 were obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band products provided by the National Oceanic and Atmospheric Administration (NOAA) and are publicly available at https://eogdata.mines.edu/products/vnl/.

Derived datasets and analytical outputs generated during this study, including residual malaria burden uncertainty estimates, school-age population estimates for IPTsc targeting, and healthcare accessibility classifications, are available from the corresponding author upon reasonable request.

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Not applicable.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	
SMC	Seasonal Malaria Chemoprevention
CPI	Chemoprevention Priority Index
ODS	Operational Deprivation Score
CIS	Cost Intensity Score
DUS	Denominator Uncertainty Score
U5	Under-Five Children
LGA	Local Government Area
RI	Routine Immunization
OSM	OpenStreetMap
NHFR	National Health Facility Registry

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