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Geospatial Prioritization and Cost-Effective Delivery of Seasonal Malaria Chemoprevention for Under-Five Children in Sokoto State, Nigeria.

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Received: 15.02.2026
Revised: 19.05.2026
Accepted: 28.05.2026
Published: 02.06.2026

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Abstract

Seasonal malaria chemoprevention (SMC) is a highly effective intervention for reducing malaria morbidity and mortality among children under five years of age in the Sahel; however, its implementation is constrained by geographic inaccessibility, dispersed settlements, and limited healthcare infrastructure. This study developed an integrated geospatial framework for ward-level operational planning and costing of malaria chemoprevention in Sokoto State, Nigeria. Household microcensus data, GRID3 settlements, WorldPop population estimates, malaria surveillance records, health facility locations, OpenStreetMap road networks, travel-time indicators, and malaria transmission metrics were integrated to quantify chemoprevention priority, operational deprivation, delivery modality, and program costs. A total of 244 wards and 10,592 settlements comprising 762,317 children under five years of age were evaluated. The chemoprevention priority index exhibited substantial spatial heterogeneity, with high-priority wards concentrated in Gada, Sabon Birni, Isa, Tangaza, and Wurno. The mean travel time to the nearest health facility ranged from less than 5 min to 163.2 min, while the number of health facilities per ward varied from 0 to 15. Fixed-session delivery was recommended for 76.2% of children, outreach services for 14.6%, mobile teams for 6.9%, and temporary nodal centers for 1.5%. The estimated programme cost was USD 1.10 million per SMC cycle and USD 4.39 million annually, with annual LGA costs ranging from approximately USD 45,000 to USD 346,561. The findings demonstrate that malaria chemo-

prevention needs and delivery costs are highly location specific and that geospatially targeted operational strategies can improve the efficiency, equity, and financial prioritization of malaria interventions in high-burden settings.

Keywords: seasonal malaria chemoprevention; missed children; denominator uncertainty; precision public health; geospatial targeting

1. Introduction

Malaria remains one of the leading causes of morbidity and mortality among children under five years of age in sub-Saharan Africa despite substantial progress in prevention and treatment over the past two decades [1]. In 2024, the African Region accounted for more than 90% of all malaria cases and deaths worldwide, with Nigeria alone contributing the largest share of the global burden [2]. Seasonal malaria chemoprevention (SMC), which involves the intermittent administration of sulfadoxine–pyrimethamine plus amodiaquine to children during the high-transmission season, has emerged as one of the most cost-effective interventions for reducing childhood malaria morbidity and mortality in the Sahel region [3,4]. However, achieving equitable SMC coverage remains challenging because operational strategies are often designed at coarse administrative scales and do not adequately account for local variations in settlement distribution, healthcare accessibility, and child vulnerability [5,6].

Recent advances in geospatial data science have enabled the integration of household microcensus surveys, gridded population estimates, settlement databases, transportation networks, and health facility inventories to improve the targeting of malaria interventions [7–9]. Studies have shown that travel time to health facilities and settlement isolation are strongly associated with inequalities in healthcare utilization and childhood health outcomes [10,11]. Similarly, high-resolution population datasets such as WorldPop and GRID3 have been increasingly used to estimate target populations and identify underserved communities [12,13]. Nevertheless, important discrepancies often exist between operational household enumeration and modeled population estimates, creating uncertainty in programme denominators and potentially leading to under- or overallocation of resources [14].

Several competing perspectives exist regarding the optimal strategy for delivering SMC in geographically heterogeneous settings. Conventional approaches emphasize fixed-facility delivery and uniform operational planning across administrative units [15]. In contrast, recent studies argue that delivery modalities should be adapted to local accessibility conditions and settlement structures through combinations of fixed sessions, outreach activities, mobile teams, and temporary service hubs [16]. However, empirical frameworks that simultaneously integrate malaria burden, accessibility, healthcare infrastructure, settlement complexity, and programme costs to guide operational decision-making remain scarce, particularly in high-burden settings in northern Nigeria [17].

Sokoto State in northwestern Nigeria provides an important case study for addressing these challenges. The state experiences highly seasonal malaria transmission, substantial spatial heterogeneity in healthcare accessibility, and considerable variation in settlement density and immunization coverage. Moreover, operational household microcensus data, malaria surveillance records, geolocated settlements, health facility inventories, and transportation datasets are available, creating a unique opportunity to develop evidence-based operational planning frameworks [18].

Therefore, this study aimed to develop an integrated geospatial framework for ward-level operational planning and costing of malaria chemoprevention in Sokoto State. Specifically, the study (i) identified priority wards requiring intensified malaria chemoprevention by integrating malaria burden, child vulnerability, healthcare accessibility, and settlement characteristics; (ii) determined the most appropriate delivery modalities, including fixed sessions, outreach services, mobile teams, and temporary nodal centers; and (iii) estimated ward- and LGA-level programme costs and delivery efficiency under alternative operational scenarios. The results demonstrate substantial spatial heterogeneity in operational needs and financial requirements and highlight the importance of ge-

ographically targeted delivery strategies for maximizing the impact and equity of malaria chemoprevention programs.

2. Materials and methods

2.1 Study area

Sokoto State is located in northwestern Nigeria between latitudes approximately 11°30′N and 13°58′N and longitudes 4°08′E and 6°54′E (Figure 1). The state covers an area of approximately 25,973 km² and is administratively divided into 23 local government areas (LGAs) and 244 wards. The state lies within the Sudan savanna ecological zone and experiences a semiarid tropical climate characterized by a rainy season from May to October and a dry season from November to April. The annual rainfall ranges from approximately 500–800 mm, while the mean annual temperature varies between 28°C and 34°C.

Malaria transmission in Sokoto State is highly seasonal and predominantly caused by Plasmodium falciparum, with transmission intensifying during and immediately after the rainy season. Seasonal malaria chemoprevention (SMC) is therefore implemented annually to protect children under five years of age during the high-transmission period. Sokoto State was selected for this study because high-resolution household microcensus data, GRID3 settlement locations, WorldPop population estimates, malaria surveillance records, health facility inventories, transportation networks, and travel-time data are simultaneously available. This combination of datasets provides a unique opportunity to develop a geospatial framework for ward-level operational planning and the cost of malaria chemoprevention interventions.

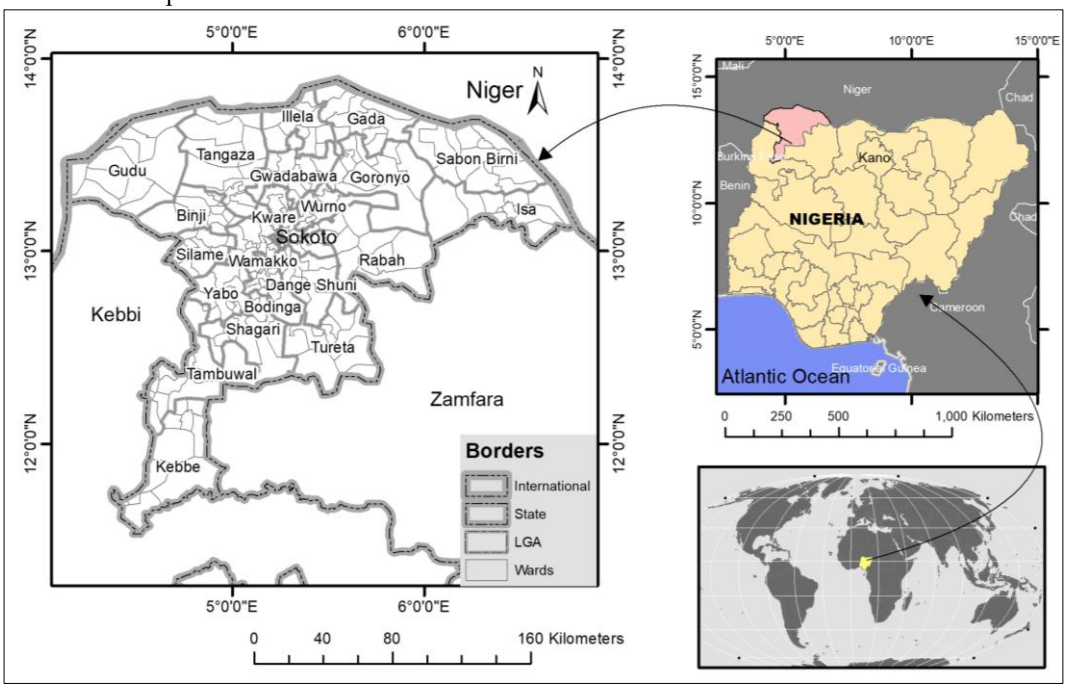

Figure 1. Location of Sokoto State in Nigeria and the distribution of the 23 local government areas (LGAs) included in this study. The map was produced by the authors via R version 4.5.1, and administrative boundary data were obtained from OCHA Nigeria.

2.2 Study design

The framework integrates multiple geospatial and epidemiological datasets, including under-five settlement populations, the chemoprevention priority index (CPI), health facility locations and types, OpenStreetMap (OSM) road networks, travel times to health facilities, routine immunization zero-dose (RI ZD) children, and administrative boundaries. These datasets are merged into an integrated spatial database from which priority wards are identified and operational deprivation is quantified. On the basis of malaria burden, accessibility, healthcare availability, and settlement

characteristics, wards are assigned to one of four operational delivery modalities: fixed sessions, outreach sessions, mobile teams, or temporary nodal centers combined with mobile teams. The selected delivery strategies are subsequently translated into financial estimates, including drug and delivery costs, operational setup costs, team capacity requirements, cost per child, annual programme cost, delivery efficiency, and investment priorities. The framework provides an evidence-based approach for optimizing malaria chemoprevention delivery and resource allocation in geographically heterogeneous and underserved settings.

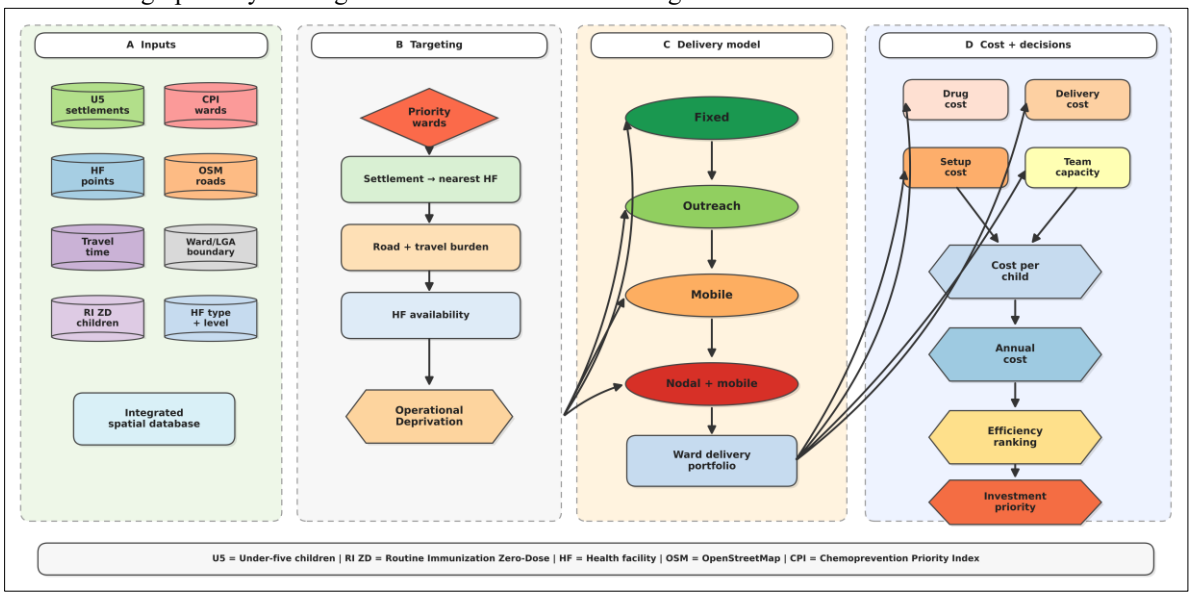

Figure 2. Conceptual framework for ward-level operational delivery planning and costing of malaria chemoprevention in Sokoto State, Nigeria.

2.2 Data used

Table 1 summarizes the geospatial, epidemiological, demographic, healthcare, and operational datasets used in this study. The analysis integrated household microcensus records, GRID3 settlement locations, WorldPop gridded population datasets, malaria surveillance data, malaria transmission indicators, healthcare infrastructure, transportation networks, and socioeconomic proxies to support ward-level operational planning and the cost of malaria chemoprevention in Sokoto State. Household microcensus and WorldPop datasets were used to characterize the underfive population distribution and quantify denominator uncertainty, whereas RHIS/DHIS2 malaria records provided information on underfive malaria mortality, severe malaria burden, and treatment coverage. Health facility locations, facility types, travel times, and OpenStreetMap road networks were incorporated to assess healthcare accessibility and operational feasibility. Additional indicators, including routine immunization zero-dose prevalence, malaria transmission intensity, and nighttime light data, were used to characterize child vulnerability and contextual socioeconomic conditions. Together, these datasets enabled the integrated assessment of malaria burden, operational deprivation, delivery modality selection, and financial requirements for geographically targeted malaria chemoprevention interventions across Sokoto State, Nigeria.

Table 1 Data Summary

Data Name	Data Type	Purpose	Source
Household Microcensus	Vector (Point)	Household enumeration	Sett. Microcensus [19]
GRID3 Settlements	Vector (Point)	Characterization of settlement	GRID3 [20]
OSM Road Network	Vector (Line)	Road accessibility analysis	OpenStreetMap [25]
Health Facilities	Vector (Point)	Healthcare service availability, facility type, and operational support	National Health Facility Registry (NHFR) [26]
Household-Enumerated Under-Five Population	Aggregated Ward Indicator	Operational denominator for malaria interventions and child vulnerability assessment	Derived from Settlement Microcensus [19]
Under5 Population (2025)	Raster (100 m)	Modeled denominator	WorldPop [21]
Raster-Derived Total Population (2025)	Raster (100 m)	Population contextualization and comparison with operational estimates	WorldPop [21]
Malaria Deaths (2014–2024)	Vector	Historical mortality analysis and prediction of 2025 underfive malaria mortality	RHIS/DHIS2 [18]
Severe Malaria Cases	Vector (LGA)	Estimation of malaria burden	RHIS/DHIS2 [18]
Severe Malaria Treated with Artesunate	Vector (LGA)	Assessment of treatment coverage and treatment gaps	RHIS/DHIS2 [18]
Chemoprevention Priority Index (CPI)	Composite Indicator	Identification of wards requiring intensified malaria chemoprevention	Derived
Operational Deprivation Score (ODS)	Composite Indicator	Quantification of operational barriers to malaria chemoprevention delivery	Derived
RI Zero-Dose Children	Ward Indicator	Assessment of immunization deprivation	Sett. Microcensus [19]
RI Zero-Dose Rate (U5)	Derived Indicator	Childhood immunization vulnerability	Sett. Microcensus [19]
Not Vaccinated Children	Ward Indicator	Assessment of immunization exclusion	Sett. Microcensus [19]
Not Vaccinated Rate	Derived Indicator	Quantification of immunization deprivation	Sett. Microcensus [19]
Fully Vaccinated Rate	Derived Indicator	Assessment of immunization performance	Sett. Microcensus [19]
Travel Time	Ward Indicator	Accessibility assessment	Sett. Microcensus [19]
Health Facility Count	Derived Ward	Healthcare service availability	Derived from NHFR [26]
Health Facility Type	Categorical	Characterization of service capacity.	NHFR [26]
PfPR 2024	Raster	*Plasmodium falciparum* parasite prevalence	Malaria Atlas Project [22]
PfIR 2024	Raster	*Plasmodium falciparum* infection intensity	Malaria Atlas Project [22]
PfMR 2024	Raster	*Plasmodium falciparum* mortality burden	Malaria Atlas Project [22]
PfIC 2024	Raster	Clinical malaria incidence	Malaria Atlas Project [22]
PfMC 2024	Raster	Clinical malaria burden	Malaria Atlas Project [22]
Nighttime Lights 2025	Raster	Proxy for socioeconomic development	NOAA VIIRS [23]
Boundaries	Vector	Spatial aggregation	OCHA Nigeria [24]

Abbreviations: U5 = Underfive children; CPI = Chemoprevention Priority Index; ODS = Operational Deprivation Score; RI = Routine Immunization; PfPR = *Plasmodium falciparum* Parasite Rate; PfIR = *Plasmodium falciparum* Infection Rate; PfMR = *Plasmodium falciparum* Mortality Rate; PfIC = *Plasmodium falciparum* Incidence Cases; PfMC = *Plasmodium falciparum* Malaria Cases; RHIS = Routine Health Information System; DHIS2 = District Health Information System 2; GRID3 = Geo-Referenced Infrastructure and Demographic Data for Development; NHFR = National Health Facility Registry; VIIRS = Visible Infrared Imaging Radiometer Suite; OSM = OpenStreetMap.

2.3 Ward-level Operational Delivery Planning for Malaria Chemoprevention

An operational delivery planning framework was developed to identify the most suitable malaria chemoprevention delivery strategy for each ward in Sokoto State, Nigeria. The framework integrated settlement microcensus data, malaria burden indicators, healthcare infrastructure, travel accessibility, and transportation networks. All spatial analyses and visualizations were performed in R version 4.5.1 via the sf, terra, dplyr, tidyr, ggplot2, patchwork, and RColorBrewer packages.

Settlement microcensus records were spatially joined to ward boundaries to derive ward-level estimates of the underfive population ($U5_i$), routine immunization (RI) zero-dose prevalence, settlement count, household count, and mean travel time to the nearest health facility. Health facility locations from the National Health Facility Registry (NHFR) were spatially intersected with wards to determine healthcare availability and facility composition. OpenStreetMap (OSM) road networks are classified into primary, secondary, tertiary, residential, track, footpath, and other categories to characterize transportation accessibility and settlement connectivity.

To allow direct comparison among indicators with different measurement units, all variables were standardized to a common 0–100 scale via min–max normalization:

$$X_i^* = 100 \times \frac{X_i - \min(X)}{\max(X) - \min(X)} \quad (1)$$

where X_i^* is the standardized value of variable X_i for ward i and where $\min(X)$ and $\max(X)$ denote the minimum and maximum values observed across all wards, respectively.

A **chemoprevention priority index (CPI)** was developed to identify wards requiring intensified malaria prevention efforts. The CPI integrates five dimensions: malaria burden, child vulnerability, treatment and access deficits, settlement complexity, and denominator uncertainty:

$$CPI_i = w_1 MBC_i + w_2 CVC_i + w_3 ATDC_i + w_4 SCC_i + w_5 DUS_i \quad (2)$$

where MBC is the Malaria Burden Component, CVC is the child vulnerability component, $ATDC$ is the access and treatment deficit component, SCC is the settlement complexity component, and DUS is the denominator uncertainty score. Equal weights ($w_j = 0.20$) were assigned to each component to avoid subjective prioritization and ensure balanced contributions.

An operational deprivation score (ODS) was subsequently developed to quantify implementation challenges by combining malaria priority, travel accessibility, healthcare availability, and the burden of difficult-to-reach populations:

$$ODS_i = \frac{CPI_i + TT_i^* + MD_i^* + (100 - HF_i^*)}{4} \quad (3)$$

where TT_i^* is the standardized mean travel time to the nearest health facility, MD_i^* is the proportion of children requiring mobile or nodal delivery, and HF_i^* is the standardized health facility availability score.

On the basis of the CPI, ODS, travel time, and healthcare accessibility, wards were assigned to one of four operational delivery categories:

i. **Fixed-session dominant**, representing wards with adequate healthcare infrastructure and short travel times;
ii. **Outreach dominant**, representing wards with moderate accessibility constraints;
iii. **Mobile-team dominant**, representing wards with dispersed settlements and poor healthcare access; and
iv. **A temporary nodal center combined with mobile teams** represents wards characterized by high CPI, long travel times, and limited healthcare infrastructure.

This operational typology provides geographically explicit guidance for implementing seasonal malaria chemoprevention (SMC) and other child survival interventions.

2.4 Cost intensity and financial requirements for Malaria chemoprevention

Objective 2 translated the operational delivery recommendations into ward-level and LGA-level financial requirements. Cost estimates were developed for the four operational delivery modalities identified in Objective 1: fixed sessions, outreach sessions, mobile teams, and temporary nodal centers.

2.4.1 Cost Assumptions

The costing framework adopted a scenario-based approach using standardized operational assumptions implemented in R. Because detailed program expenditure data were unavailable for all delivery modalities, the estimates are intended to provide indicative costs for operational planning rather than exact program expenditures.

Drug procurement costs were assumed to be USD 0.90 per child per SMC cycle. The delivery costs excluding drugs were assumed to be as follows:

- Fixed session: USD 0.35 per child per cycle
- Outreach session: USD 0.85 per child per cycle
- Mobile team: USD 1.50 per child per cycle
- Temporary nodal center: USD 1.20 per child per cycle

Additional operational setup costs were included to account for transportation, logistics, supervision, and coordination. The setup cost per delivery session was assumed to be as follows:

- Fixed session: USD 10
- Outreach session: USD 35
- Mobile team: USD 65
- Temporary nodal center: USD 55

Furthermore, a supervision cost of USD 25 per ward and a planning cost of USD 20 per **ward** were incorporated.

The operational capacities of delivery teams were assumed as follows:

- Fixed session: 250 children per day
- Outreach session: 180 children per day
- Mobile team: 120 children per day
- Temporary nodal center: 160 children per day

The number of delivery sessions required for ward $i$was estimated as:

$$N_{sessions,i} = \left\lceil \frac{U5_i}{Capacity} \right\rceil \quad (4)$$

where $U5_i$ is the number of children under five in ward i, capacity is the number of children reached by a delivery team per day, and [.] denotes the ceiling function.

2.4.2 Cost Estimation

The total cost per SMC cycle for ward i was estimated as the sum of the variable and operational setup costs:

$$TC_i = VC_i + SC_i \quad (5)$$

where TC_i is the total cost per cycle, VC_i is the variable cost associated with drug procurement and service delivery, and SC_i is the operational setup cost.

The cost per child per SMC cycle was calculated as:

$$CPC_i = \frac{TC_i}{U5_i} \quad (6)$$

where CPC_i is the cost per child per cycle (USD) and where $U5_i$ is the number of eligible children under five.

Annual programme costs were estimated assuming four SMC cycles per year:

$$AC_i = 4 \times TC_i \quad (7)$$

The annual cost per child was computed as:

$$ACPC_i = \frac{AC_i}{U5_i} \tag{8}$$

where AC_i is the annual programme cost and where $ACPC_i$ is the annual cost per child.

To identify wards requiring disproportionately high investments, a cost intensity score (CIS) was developed by integrating annual cost, annual cost per child, chemoprevention priority, and operational deprivation:

$$CIS_i = \frac{AC_i^* + ACPC_i^* + CPI_i + ODS_i}{4} \tag{9}$$

where AC_i^* and $ACPC_i^*$ represent the standardized annual cost and standardized annual cost per child, respectively.

Delivery efficiency was evaluated as the number of children reached per dollar invested:

$$DE_i = \frac{U5_i}{AC_i} \tag{10}$$

where higher values indicate more cost-efficient delivery systems.

Ward-level results were subsequently aggregated to the LGA level to estimate the total annual financial requirement:

$$AC_{LGA} = \sum_{i=1}^{n} A\,C_i \tag{11}$$

where n is the number of wards within an LGA.

The integrated framework enabled simultaneous assessment of epidemiological priority, operational feasibility, and financial requirements, thereby providing an evidence-based basis for prioritizing investments and designing equitable malaria chemoprevention strategies in Sokoto State.

3. Results

3.1 Priority wards and settlements that require special delivery support for malaria chemoprevention

3.1.1 Ward-level Operational Delivery Planning for Malaria Chemoprevention

The operational delivery planning framework integrates chemoprevention priority, travel time, health facility availability, road accessibility, and settlement characteristics to identify the most suitable delivery strategy for each ward in Sokoto State. A total of 244 wards across 23 LGAs were evaluated. The chemoprevention priority index (CPI) ranged from 0--100, with a median value of approximately 55 and an upper quartile exceeding 70, indicating substantial spatial heterogeneity in malaria prevention needs. High-priority wards were concentrated in northern and eastern LGAs, particularly Gada, Sabon Birni, Isa, Tangaza, and parts of Wurno and Gwadabawa, whereas lower priority wards occurred mainly in western LGAs, such as Gudu and Silame (Figure 3a).

The mean settlement travel time to the nearest health facility varied markedly across wards, ranging from less than 5 min to 163.2 min, with several wards in Tureta, Rabah, and Eastern Sokoto exhibiting travel times above 80 min (Figure 3b). Health facility availability also displayed pronounced disparities. The number of health facilities per ward ranged from 0--15, with a median of approximately three facilities. The highest concentrations of facilities were observed around Sokoto North, Sokoto South, Wamakko, and parts of Gwadabawa, whereas peripheral wards in Isa, Sabon Birni, Tangaza, and Gudu had comparatively sparse coverage (Figure 3c).

The integration of malaria burden, travel accessibility, and healthcare infrastructure resulted in four recommended operational delivery modes (Figure 3d). Fixed-session delivery dominated most wards, particularly in urban and peri-urban areas with relatively good healthcare access. Outreach delivery was recommended for moderately accessible wards, whereas mobile teams and tem-

porary nodal centers were concentrated in remote wards characterized by long travel times and high chemoprevention needs. Temporary nodal centers combined with mobile teams were particularly recommended in parts of Tureta, Shagari, Bodinga, and selected wards in Gada and Isa, where both access barriers and childhood vulnerability were pronounced.

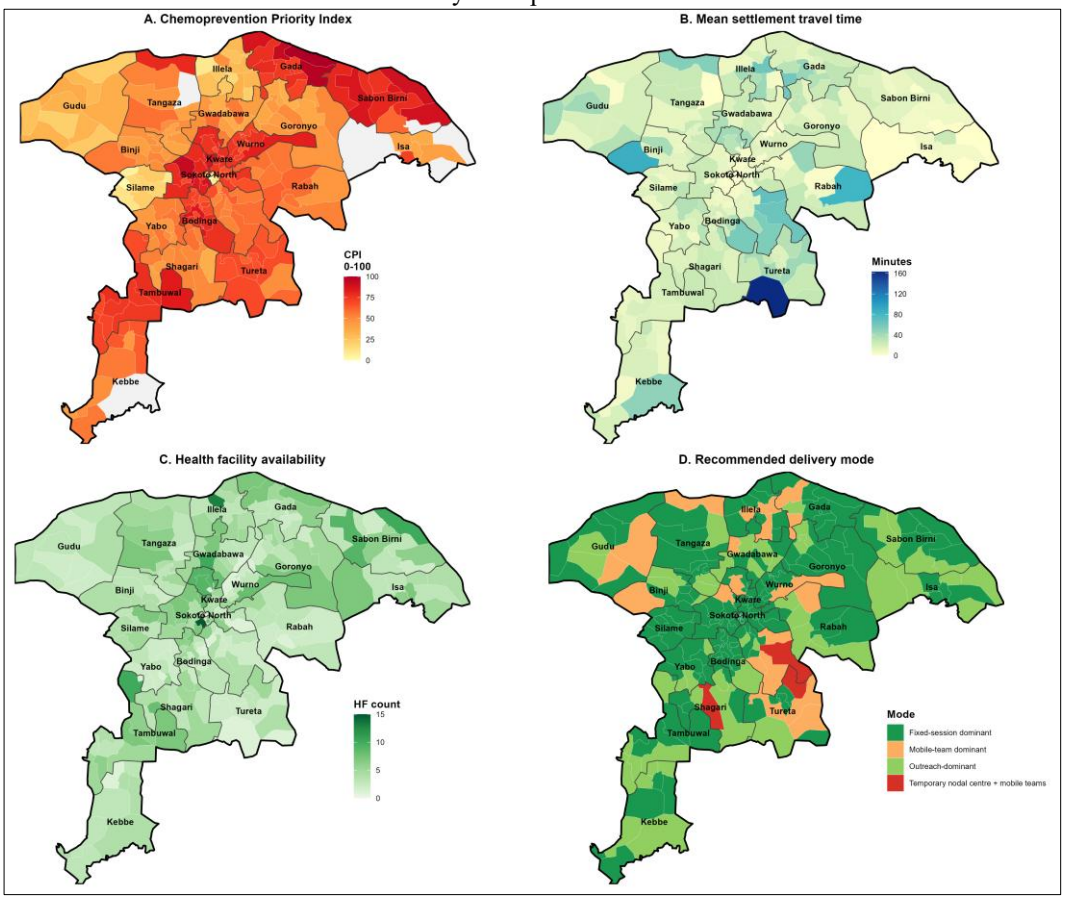

Figure 3. Ward-level operational delivery planning for malaria chemoprevention in Sokoto State, Nigeria: (a) chemoprevention priority index (CPI); (b) mean settlement travel time to the nearest health facility; (c) health facility availability; and (d) recommended operational delivery mode on the basis of integrated burden, accessibility, and infrastructure indicators.

3.1.2 Operational Deprivation Score and Priority Classification

To further quantify implementation challenges, an operational deprivation score (ODS) was developed by integrating chemoprevention priority, travel time, mobile and nodal delivery requirements, healthcare availability, and hard-to-reach settlement characteristics. The ODS varied substantially among wards, ranging from approximately 15--71.6%, with a median value of approximately 34. The wards with the highest deprivation scores were concentrated in Tureta, Dange Shuni, Binji, and Wurno, and the wards of Sokoto North and Bodinga were selected (Figure 4a).

The classification of operational deprivation revealed marked spatial heterogeneity (Figure 4b). Approximately one-fifth of the wards fell into the "very high" deprivation category, while another substantial proportion were classified as "high". Conversely, urban wards surrounding Sokoto metropolises generally presented lower deprivation levels owing to shorter travel times, denser road networks, and greater health facility availability.

Among the most deprived wards, Soron Yamma (Binji LGA) recorded a mean RI zero-dose rate of 93.1%, whereas Wababe-Salau, Ge Ere Gajara, and Fajaldu in Dange Shuni LGA presented RI zero-dose rates exceeding 90%. Dangulbi (Tureta LGA) combined high deprivation with an extensive road network (149.8 km) and an RI zero-dose rate of 78.7%, suggesting considerable operational complexity despite reasonable physical connectivity.

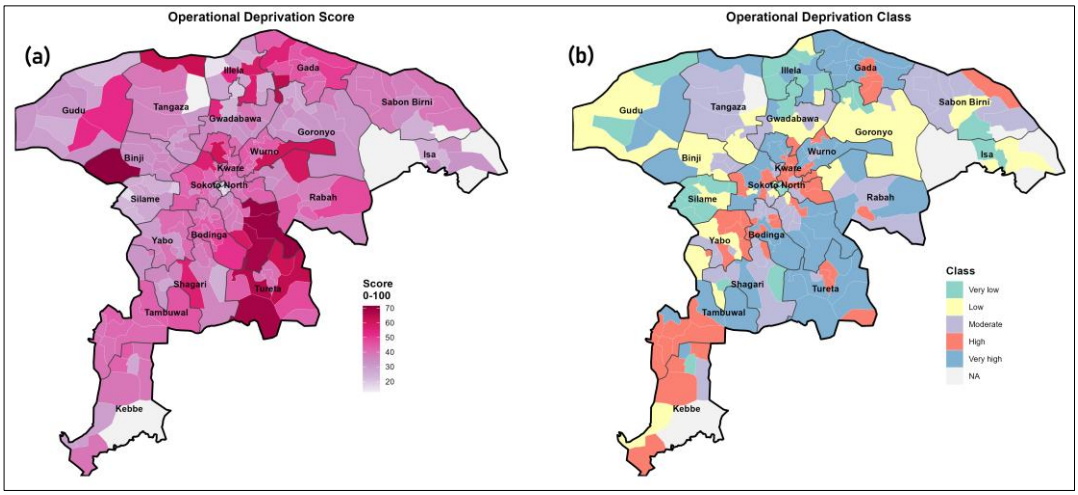

Figure 4. Ward-level operational deprivation for malaria chemoprevention delivery in Sokoto State: (a) Operational deprivation score (ODS) and (b) Operational deprivation class.

3.1.3 Road Network Accessibility and Health Facility Distribution

The OSM-derived transport network revealed substantial spatial variation in road accessibility across Sokoto State (Figure 5).

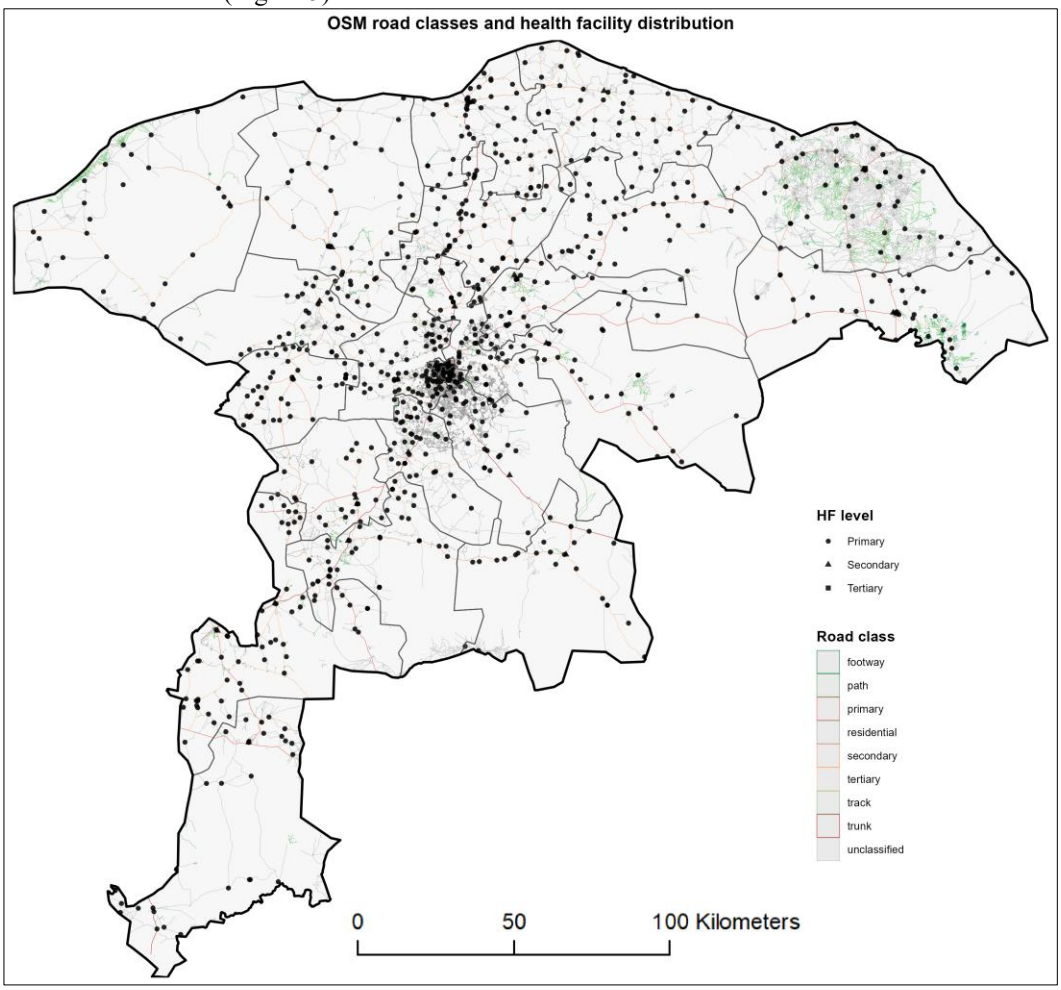

Figure 5. Spatial distribution of the OSM road classes and health facilities in Sokoto State, showing the locations and hierarchy of healthcare facilities overlaid on the transport network.

Across the 244 wards, the total road length ranged from less than 10 km to 863.2 km, with a median value of 64.7 km. Track and path networks constituted the majority of road infrastructure,

with median lengths of 36.7 km per ward, whereas primary and secondary roads were sparse outside major population centers.

Similarly, health facilities were unevenly distributed. Among the 242 wards with healthcare infrastructure, the number of facilities ranged from 1--15, with primary healthcare facilities accounting for the majority of services. Public facilities dominated the healthcare landscape, whereas secondary facilities were scarce and largely concentrated in urban centers. The spatial coincidence of sparse road networks and limited health facility availability in remote northern and eastern wards highlights substantial operational constraints for delivering seasonal malaria chemoprevention.

3.1.4 Settlement-level recommended delivery modes

A total of 10,592 microcensus settlements were assessed to determine the most appropriate malaria chemoprevention delivery strategy (Figure 6).

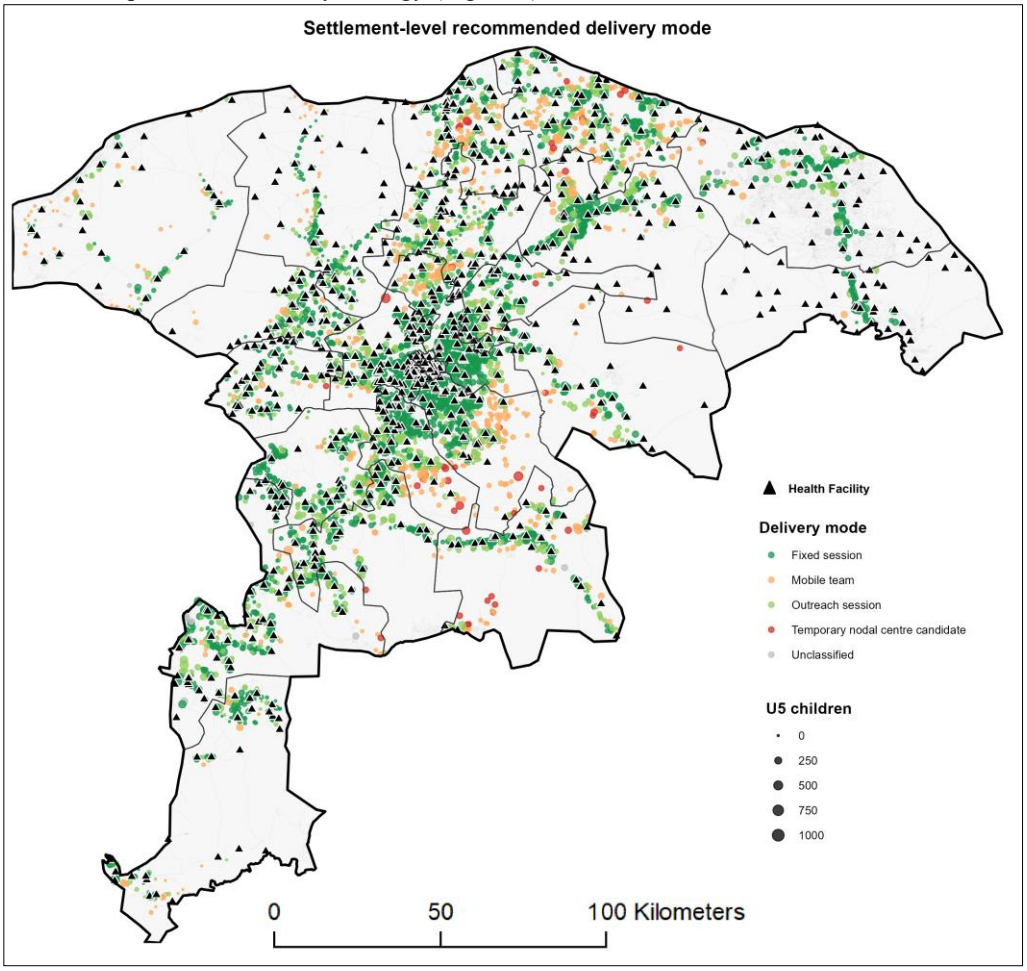

Figure 6. Settlement-level recommended delivery mode for malaria chemoprevention in Sokoto State. The symbol color indicates the recommended delivery strategy, whereas the symbol size represents the number of children under five years of age residing in each settlement.

Fixed-session delivery represented the dominant strategy and was concentrated around wards with established healthcare infrastructure. Outreach delivery was common in settlements located at intermediate travel times, whereas mobile teams and temporary nodal centers were preferentially assigned to isolated settlements characterized by poor accessibility and limited facility coverage.

The settlement-level analysis demonstrated that mobile and nodal delivery requirements were not uniformly distributed across the state. Rather, clusters of settlements require specialized delivery modes.

Table 2 LGAwise count of Operational_Mode and the sum of U5_Children

LGA/Operational_Mode	Count	Sum of U5_Children
Binji	10	14126
Fixed-session dominant	6	10002
Mobile-team dominant	1	72
Outreach-dominant	3	4052
Bodinga	11	35158
Fixed-session dominant	10	30237
Outreach-dominant	1	4921
Dange Shuni	11	38393
Fixed-session dominant	5	17626
Mobile-team dominant	3	8435
Outreach-dominant	2	7321
Temporary nodal center + mobile teams	1	5011
Gada	11	55597
Fixed-session dominant	8	43870
Mobile-team dominant	2	6570
Outreach-dominant	1	5157
Goronyo	11	60105
Fixed-session dominant	9	47329
Outreach-dominant	2	12776
Gudu	10	11275
Fixed-session dominant	6	6258
Mobile-team dominant	2	3935
Outreach-dominant	2	1082
Gwadabawa	11	30089
Fixed-session dominant	5	15729
Mobile-team dominant	1	5045
Outreach-dominant	5	9315
Illela	11	28085
Fixed-session dominant	8	22478
Mobile-team dominant	3	5607
Isa	10	34342
Fixed-session dominant	5	34046
Outreach-dominant	5	296
Kebbe	10	16982
Fixed-session dominant	5	8769
Outreach-dominant	5	8213
Kware	11	63321
Fixed-session dominant	10	57644
Mobile-team dominant	1	5677
Rabah	11	31838

Fixed-session dominant	5	15468
Mobile-team dominant	1	190
Outreach-dominant	5	16180
Sabon Birni	11	45556
Fixed-session dominant	7	36559
Outreach-dominant	4	8997
Shagari	10	34012
Fixed-session dominant	6	20774
Outreach-dominant	3	9622
Temporary nodal center + mobile teams	1	3616
Silame	10	14194
Fixed-session dominant	10	14194
Sokoto North	11	32344
Fixed-session dominant	11	32344
Sokoto South	11	28848
Fixed-session dominant	11	28848
Tambuwal	11	45871
Fixed-session dominant	6	27023
Outreach-dominant	5	18848
Tangaza	10	6909
Fixed-session dominant	6	6058
Mobile-team dominant	1	9
Outreach-dominant	3	842
Tureta	10	24680
Fixed-session dominant	5	10838
Mobile-team dominant	3	8432
Outreach-dominant	1	2337
Temporary nodal center + mobile teams	1	3073
Wamakko	11	50409
Fixed-session dominant	10	47623
Mobile-team dominant	1	2786
Wurno	11	34306
Fixed-session dominant	10	28581
Mobile-team dominant	1	5725
Yabo	10	25877
Fixed-session dominant	7	18760
Outreach-dominant	3	7117
Grand Total	244	762317

3.1.5 LGA-Level Mobile and Nodal Delivery Burden

The aggregation of settlement-level recommendations to the LGA level revealed substantial differences in operational requirements across Sokoto State. The proportion of underfive children requiring either mobile teams or temporary nodal centers ranged from 0% to 46.6% across LGAs. LGAs with the greatest operational burden also presented elevated chemoprevention priority scores and higher operational deprivation levels, indicating that malaria burden, healthcare access, and delivery complexity are spatially interconnected.

The target ward prevalence varies considerably among LGAs. For example, Gada recorded target wards in all of its wards (100%), whereas Bodinga reported a target ward rate of 63.6%. The mean CPI values across LGAs ranged from approximately 50--82, with the highest values occurring in LGAs characterized by elevated travel times and lower healthcare accessibility. These findings suggest that operational resources should be preferentially allocated to LGAs where a large proportion of children depend on mobile or nodal delivery strategies.

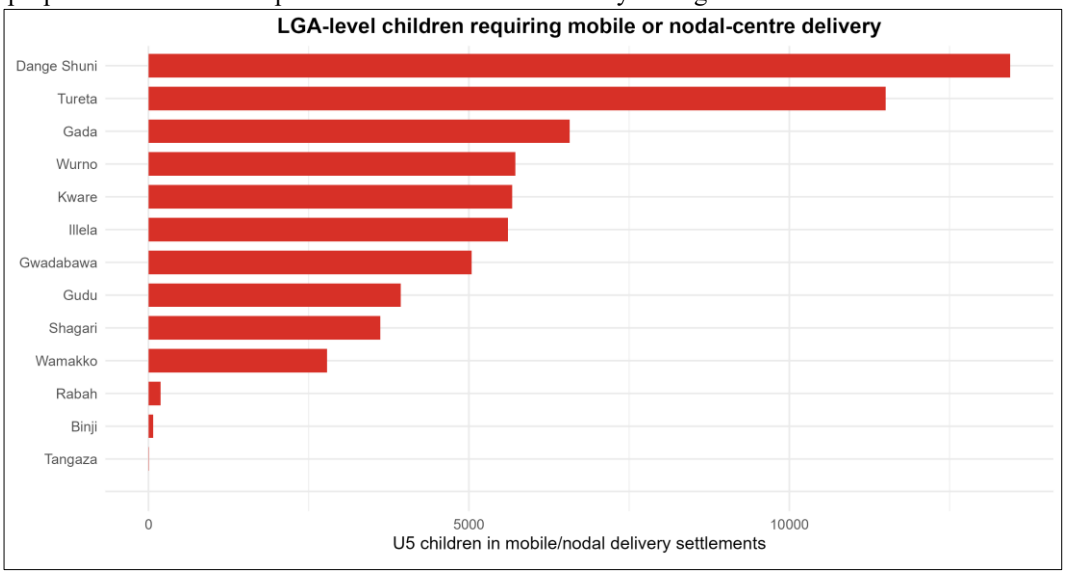

Figure 7. LGA-level burden of mobile-team and temporary nodal-center delivery for malaria prevention, showing the number and proportion of underfive children requiring specialized delivery approaches across Sokoto State.

3.2 Cost Intensity and Financial Requirements for Ward-Level Chemoprevention Delivery

The cost analysis translated the operational delivery strategies developed in Objective 1 into ward- and LGA-level financial requirements for malaria chemoprevention. Using the delivery assumptions, the analysis estimated the costs associated with fixed sessions, outreach services, mobile teams, and temporary nodal centers.

Across Sokoto State, a total of 762,317 under five children residing in 244 wards were considered eligible for chemoprevention. Of these, 581,058 children (76.2%) were assigned to fixed-session delivery, 111,338 (14.6%) to outreach services, 52,483 (6.9%) to mobile teams, and 11,700 (1.5%) to temporary nodal centers. The estimated programme cost was USD 1.10 million per SMC cycle and USD 4.39 million annually, corresponding to a mean cost of USD 1.44 per child per cycle and USD 5.75 per child per year.

The spatial patterns of delivery costs exhibited substantial heterogeneity across wards (Figure 8a).

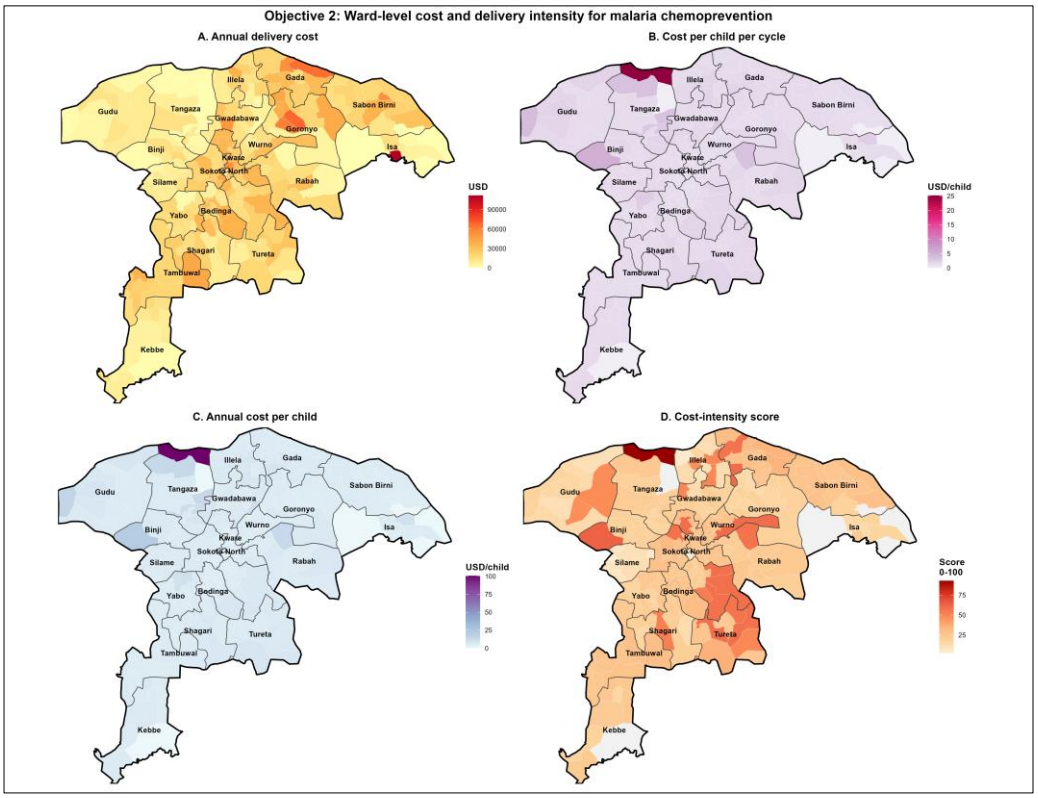

Figure 8. Ward-level cost and delivery intensity for malaria chemoprevention in Sokoto State, Nigeria: (a) estimated annual delivery cost (USD); (b) cost per child per SMC cycle; (c) annual cost per child; and (d) integrated cost–intensity score combining programme cost, delivery complexity, operational deprivation, and chemoprevention priority.

The highest annual costs were concentrated in wards with large populations under five and elevated chemoprevention priority scores. Notably, Isa South (Isa LGA) recorded the highest annual cost estimate (USD 111,995), followed by the Goronyo ward (USD 68,086), Dukamaje in Gada LGA (USD 65,379), Kagara in Goronyo LGA (USD 59,805), and Gidan Rugga More in Kware LGA (USD 55,555). The annual cost per child was relatively stable across most wards, generally ranging between USD 4 and USD 8, although several remote wards presented substantially higher costs because of their dependence on mobile or nodal delivery modes (Figure 8c).

The cost–intensity score, which combines programme cost, delivery complexity, operational deprivation, and chemoprevention priority, ranged from approximately 5--92. Wards with the highest cost intensity included Ruwa Wuri (Tangaza LGA), Soron Yamma (Binji LGA), Kiri (Gada LGA), Chacho-Marnona (Wurno LGA), and Bankanu (Kware LGA) (Figure 8d). These wards require disproportionate operational investments owing to their combination of high malaria burden, poor accessibility, and substantial mobile or nodal delivery requirements.

The classification of cost intensity and delivery efficiency further highlighted marked spatial variation (Figure 9). Approximately one-fifth of the wards were categorized as having very high cost intensity, predominantly in northern and central Sokoto. Conversely, wards exhibiting high delivery efficiency, measured as the number of children reached per dollar invested, were concentrated in areas where fixed-session delivery predominated. Remote wards characterized by difficult terrain and low settlement density generally exhibited lower delivery efficiency, indicating that achieving equitable coverage requires greater investments per child.

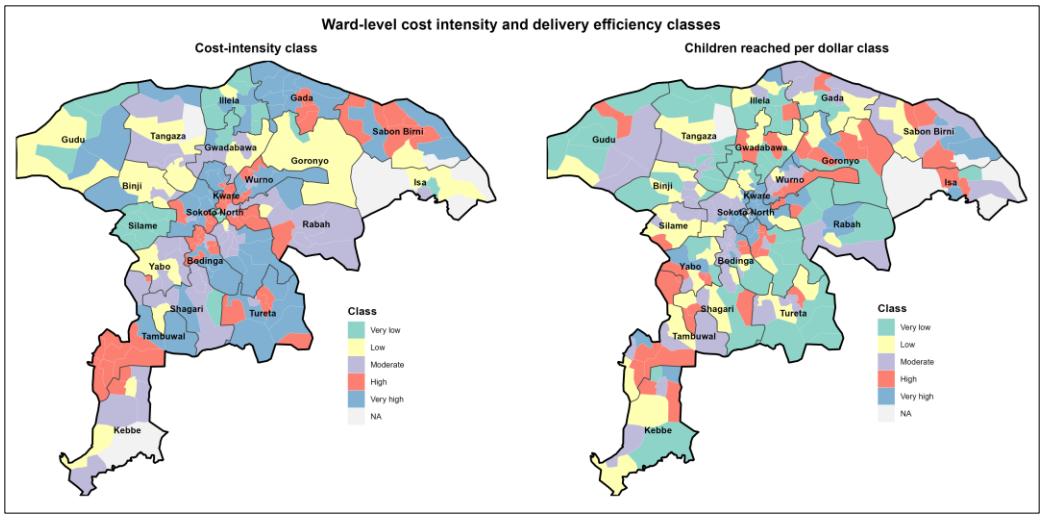

Figure 9. Ward-level cost intensity and delivery efficiency classes in Sokoto State: (a) cost-intensity class and (b) children reached per dollar class, illustrating spatial variation in the economic efficiency of malaria chemoprevention delivery.

At the LGA level, annual chemoprevention costs range from approximately USD 45,000 to more than USD 346,000 (Figure 10).

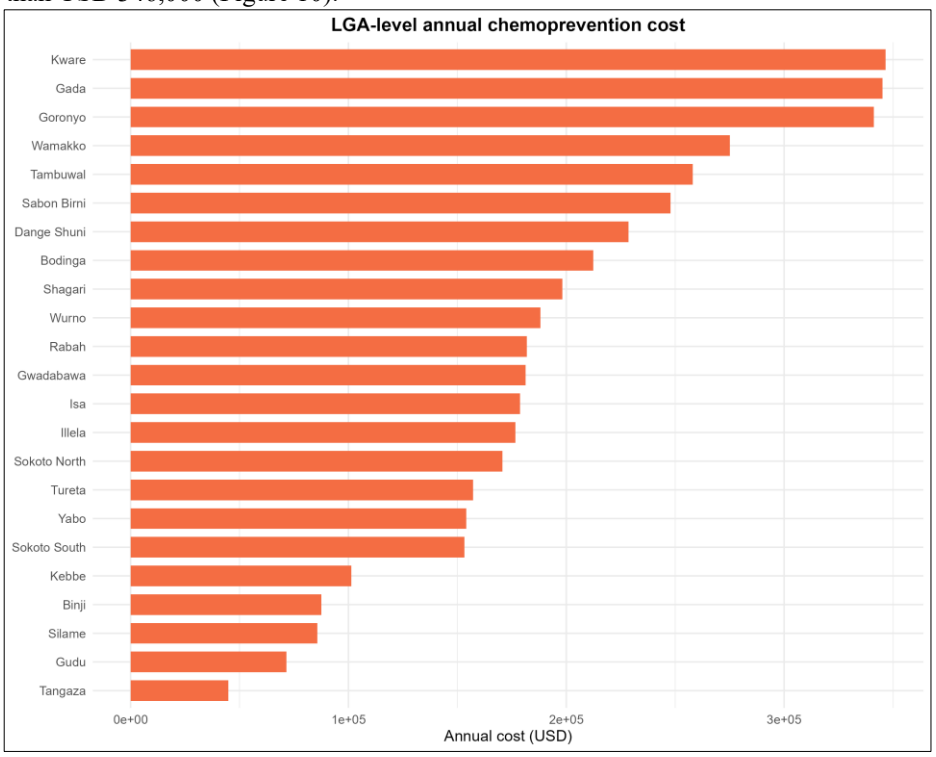

Figure 10. LGA-level annual chemoprevention cost across Sokoto State. LGAs are ranked according to the total estimated annual cost required to deliver malaria chemoprevention to the target under-five population.

Kware LGA recorded the highest annual cost (USD 346,561), closely followed by Gada (USD 345,086) and Goronyo (USD 341,129). Other LGAs with substantial financial requirements included Wamakko (USD 275,098), Tambuwal (USD 258,050), Sabon Birni (USD 247,797), and Dange Shuni (USD 228,531). In contrast, Tangaza, Gudu, Silame, and Binji presented comparatively lower overall costs because of their smaller target populations despite having pockets of high operational deprivation.

Overall, the results indicate that the financial burden of malaria chemoprevention is driven not only by the size of the target population but also by the spatial configuration of settlements, accessibility constraints, and delivery modality needed. These findings provide an operationally

relevant framework for prioritizing investments and optimizing resource allocation in geographically heterogeneous malaria-endemic settings.

4. Discussion

This study developed an integrated geospatial framework for ward-level operational planning and costing of malaria chemoprevention in Sokoto State by combining household microcensus data, settlement distributions, healthcare accessibility, malaria burden indicators, and operational cost assumptions. The findings reveal substantial spatial heterogeneity in malaria vulnerability, accessibility constraints, and programme costs, indicating that uniform intervention strategies are unlikely to achieve equitable coverage. Instead, geographically differentiated delivery modalities are required to maximize programme effectiveness and efficiency.

The identification of priority wards with high chemoprevention priority index (CPI) values in Gada, Sabon Birni, Isa, Tangaza, and Wurno is consistent with previous studies demonstrating that malaria burden and childhood vulnerability are spatially clustered in northern Nigeria [27,28]. Areas characterized by high malaria transmission intensity, poor healthcare accessibility, and elevated immunization deprivation often experience overlapping disadvantages that reduce the effectiveness of conventional facility-based interventions [29]. The present study extends these observations by showing that operational deprivation is not solely a function of malaria burden but also reflects settlement isolation, travel time, and health facility availability. This multidimensional perspective aligns with recent calls for precision public health approaches that integrate epidemiological and geospatial information to guide intervention targeting [30].

The pronounced spatial variation in travel time and healthcare accessibility observed in this study corroborates findings from previous accessibility studies across sub-Saharan Africa [31,32]. Wards with travel times exceeding one hour to the nearest health facility were disproportionately represented among those requiring mobile teams or temporary nodal centers. These results support the hypothesis that physical accessibility remains a major determinant of healthcare utilization and intervention coverage [33]. Although fixed-session delivery has traditionally been regarded as the most cost-efficient strategy, recent evidence suggests that reliance on fixed facilities alone may exacerbate inequalities in remote and underserved communities [34]. Our findings support this alternative hypothesis by demonstrating that mixed delivery strategies are necessary to achieve equitable coverage in geographically heterogeneous settings.

The operational delivery typology proposed in this study—comprising fixed sessions, outreach services, mobile teams, and temporary nodal centers—provides a practical framework for tailoring malaria interventions to local conditions. Similar adaptive delivery approaches have recently been advocated for seasonal malaria chemoprevention and routine immunization programs in the Sahel, where settlement dispersion and poor transport infrastructure limit the effectiveness of conventional delivery models [35,36]. However, most previous studies have focused either on epidemiological targeting or healthcare accessibility in isolation. By integrating both dimensions with financial analysis, the present study provides a more comprehensive basis for operational decision-making.

The cost analysis revealed that programme expenditure is influenced not only by the size of the target population but also by settlement configuration, healthcare accessibility, and the delivery modality needed. Compared with wards dominated by fixed sessions, wards relying heavily on mobile teams or temporary nodal centers presented substantially higher annual costs and lower delivery efficiency. These findings are consistent with previous economic evaluations showing that reaching the last mile of malaria interventions often requires disproportionately greater investments [37]. Nevertheless, the higher costs associated with mobile and nodal delivery should not necessarily be interpreted as inefficiencies. Rather, they may represent essential investments for reducing health inequities and improving access among populations that are routinely underserved by conventional healthcare systems [38].

An important contribution of this study is the integration of household microcensus data with modeled population estimates from WorldPop to quantify denominator uncertainty. Previous studies have shown that discrepancies between operational enumeration datasets and gridded population datasets can substantially affect program planning and resource allocation [39,40]. The present analysis confirms that denominator uncertainty varies considerably across wards and should be explicitly considered when estimating intervention targets and financial requirements. Integrating operational enumeration with gridded population products may therefore provide more robust estimates of intervention needs, particularly in rapidly changing or poorly mapped settings.

The findings of this study have important implications for malaria control programs and development partners, including organizations supporting evidence-based health investments. The operational framework enables programme managers to identify wards where investments in mobile teams, temporary nodal centers, or enhanced healthcare infrastructure are likely to produce the greatest gains in child survival. Furthermore, the ward-level cost estimates provide a transparent basis for comparing alternative implementation scenarios and prioritizing limited resources. These geographically targeted strategies are increasingly recognized as essential for accelerating progress toward malaria elimination and universal health coverage [41].

Several limitations should be acknowledged. First, the cost analysis was based on standardized operational assumptions and may not fully capture local variations in logistics, transportation costs, or workforce availability. Second, travel time estimates were derived from existing datasets and may not reflect seasonal changes in road conditions or flooding. Third, malaria burden indicators were primarily available at the LGA level and therefore may not capture fine-scale spatial heterogeneity within wards. Future studies could incorporate dynamic accessibility models, real-time mobility data, and high-resolution malaria surveillance systems to improve operational planning and cost estimation [42].

Despite these limitations, this study demonstrates the value of integrating geospatial intelligence, operational microcensus data, healthcare accessibility, and economic analysis to support precision malaria interventions. Future research should explore the incorporation of optimization algorithms, network analysis, and agent-based simulations to design adaptive delivery systems that respond to seasonal changes in malaria transmission, accessibility, and population movement. Such approaches may further increase the efficiency, equity, and sustainability of malaria chemoprevention programs in Nigeria and other high-burden settings [43].

Data availability statement:

Household Microcensus datasets, including household locations, household-enumerated under-five population estimates, routine immunization indicators, and travel time metrics, were obtained through the Nigerian Settlement Microcensus programme. These datasets are not publicly available because they contain operational and georeferenced household information but may be accessed from the implementing agencies subject to approval and data-sharing agreements.

Settlement location data were obtained from the GRID3 Nigeria settlement database, which is publicly available through the GRID3 data portal at https://data.grid3.org/.

Road network data used for accessibility analysis were obtained from OpenStreetMap and are publicly available at https://www.openstreetmap.org/ and through the Geofabrik download service at https://download.geofabrik.de/africa/nigeria.html.

Health facility locations, facility classifications, and operational support information were obtained from the Nigerian National Health Facility Registry (NHFR), publicly accessible at https://hfr.health.gov.ng/.

Raster-derived under-five population estimates and total population estimates for 2025 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/.

Malaria mortality records (2014–2024), severe malaria case records, and severe malaria cases treated with artesunate were obtained from the Nigerian Routine Health Information System (RHIS) through the District Health Information System 2 (DHIS2) platform maintained by the Federal Ministry of Health. These data are not publicly available because of national health data governance and confidentiality requirements but may be obtained from the relevant authorities subject to approval.

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

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/.

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

Derived datasets and indicators generated during this study, including the Chemoprevention Priority Index (CPI), Operational Deprivation Score (ODS), health facility counts, and accessibility metrics, are available from the corresponding author upon reasonable request.

Author Contributions: Author Contributions: Conceptualization, Y.J.C., Z.I., and U.M.I.; methodology, Z.I., Y.J.C., and U.M.I.; software, Z.I.; validation, Z.I., Y.J.C., U.M.I., and C.A.U.; formal analysis, Z.I.; investigation, Y.J.C., U.M.I., Z.I., K.U., C.V.U., C.A.U., and Y.J.D.; data curation, Z.I., U.M.I., and Y.J.C.; visualization, Z.I.; writing—original draft preparation, Z.I. and Y.J.C.; writing—review and editing, U.M.I., K.U., C.V.U., C.A.U., and Y.J.D.; supervision, Y.J.C.; project administration, Y.J.C.; resources, U.M.I., K.U., C.V.U., C.A.U., and Y.J.D. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Informed Consent Statement

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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