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Catchment-Level Spatial Inequities in Antenatal Care Utilization and Malaria Prevention in Akwa Ibom State, Nigeria.

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Abstract

Equitable maternal health and malaria prevention coverage depends on aligning service delivery with spatially heterogeneous population demand. In Nigeria, routine health indicators are rarely evaluated within fine-scale spatial frameworks that account for demographic pressure and open catchment dynamics. This study examines spatial inequities in antenatal care (ANC) utilization and malaria prevention among pregnant women in Akwa Ibom State using a catchment-based GIS approach. Health-facility catchment polygons (n = 654) were used as the primary analytical unit. First antenatal care attendance (ANC1_2025) were obtained from the national DHIS2 platform. Population denominators, including total population, women aged 15–45 years, and children aged 0–12 months were derived from WorldPop and aggregated to catchments. Annual pregnancies and pregnancy stock for 2025 were estimated using a demographic reconstruction model adjusted for infant survival and pregnancy loss. Service utilization indicators were standardized against pregnancy burden and women-of-reproductive-age density. Demand-adjusted log-linear regression and spatial autocorrelation analyses (Global Moran's I and Local Indicators of Spatial Association) were applied. Demographic demand was highly concentrated, with the top 10% of catchments accounting for 29.6% of estimated pregnancies and pregnancy stock. Catchment-level ANC utilization relative to pregnancy stock ranged from 0 to over 1,200 per 100 pregnant women, indicating pronounced spatial inequities and cross-boundary service use. The demand-adjusted model explained a meaningful share of spatial variation in ANC utilization (adjusted $R^2 = 0.169$). Spatial analysis revealed weak global autocorrelation in residuals (Moran's $I = 0.034$, $p = 0.064$) but identified localized clusters of under-utilization. Maternal health and malaria prevention services in Akwa Ibom State exhibit strong fine-scale spatial inequities that are masked by aggregated statistics. Catchment-based, demand-adjusted spatial analysis provides actionable evidence for equity-oriented planning aligned with Sustainable Development Goals 3, 10, and 11.

Keywords: Malaria in pregnancy; Intermittent preventive treatment (IPTp); Spatial analysis.

1. Introduction

Maternal health outcomes remain a critical public health challenge in sub-Saharan Africa, where preventable causes such as malaria in pregnancy and delayed antenatal care continue to drive excess maternal and neonatal morbidity and mortality. Nigeria alone accounts for a substantial share of the global maternal mortality burden, with marked subnational disparities in access to essential maternal health services (World Health Organization [WHO], 2023; UNFPA, 2022). Despite sustained policy commitments, including free antenatal services and nationwide malaria prevention programs, coverage remains uneven across geographic space, reflecting deep-seated inequalities in health system capacity, population distribution, and service accessibility (Akinyemi et al., 2021; Awofeso & Rammohan, 2022). Understanding where and why these disparities occur is essential for achieving Sustainable Development Goals (SDGs) 3.1 and 3.3.

This study examines spatial inequities in antenatal care utilization and malaria prevention services among pregnant women in Akwa Ibom State, Nigeria, using a catchment-based spatial epidemiological framework. Specifically, the analysis focuses on first antenatal care attendance (ANC1) and uptake of intermittent preventive treatment in pregnancy (IPTp3) during 2025, assessed relative to underlying demographic demand. Health facility catchments are treated as the primary analytical units, allowing service utilization to be interpreted in relation to resident pregnancy burden, women of reproductive age, and spatial scale. By integrating routine health service data with high-resolution population estimates, the study moves beyond administrative averages to reveal fine-scale patterns of service delivery and demand mismatch (Tatem, 2021; Alegana et al., 2023).

National and state-level indicators often mask substantial within-area heterogeneity in maternal health service access. Evidence increasingly shows that service utilization is shaped not only by socioeconomic factors but also by spatial processes such as facility distribution, catchment overlap, and population mobility (Weiss et al., 2020; Ray & Ebener, 2021). In malaria-endemic settings, missed opportunities for IPTp delivery during ANC visits remain common, undermining prevention efforts and exacerbating inequities among vulnerable populations (van Eijk et al., 2021; Bhatt et al., 2023). Without spatially explicit assessments, interventions risk being poorly targeted, leaving pockets of under-service unaddressed despite apparent progress at higher administrative scales.

Recent research has increasingly employed geospatial and spatial statistical methods to study maternal health service access, including travel-time modelling, facility catchment analysis, and spatial autocorrelation techniques (Maina et al., 2020; Jia et al., 2022). The use of gridded population datasets such as WorldPop has enabled more accurate estimation of population-at-risk and service demand at fine spatial scales (Bondarenko et al., 2020; Wardrop et al., 2021). Additionally, spatial regression and Local Indicators of Spatial Association (LISA) have been widely adopted to identify clusters of under- and over-performance in health service delivery (Anselin, 2020; Kang et al., 2022). These approaches provide powerful tools for linking demographic demand with observed service utilization.

Despite methodological advances, important gaps remain. Many studies rely on administrative units such as districts or LGAs, implicitly assuming homogeneous populations and closed service areas, an assumption increasingly shown to be unrealistic (Noor et al., 2021; Ouma et al., 2022). Few analyses explicitly account for the permeability of health facility catchments, where patients frequently cross boundaries in search of care. Moreover, pregnancy is often approximated using crude fertility rates or national averages, limiting the precision of demand-adjusted service indicators (Say et al., 2021). There is a growing need for approaches that integrate demographic reconstruction, spatial scale effects, and residual-based equity analysis within a single coherent framework.

To the best of our knowledge, no study has combined catchment-level pregnancy estimation, demand-adjusted ANC and IPTp intensity measures, and residual-based spatial clustering analysis to examine maternal health service equity in Akwa Ibom State. This study addresses this gap by asking:

(1) How is maternal demographic demand distributed across health facility catchments?
(2) To what extent does ANC utilization align with underlying pregnancy burden and population structure?
(3) Where do spatial clusters of under- and over-utilization persist after accounting for demographic demand?

This study advances spatial health equity analysis by integrating demographic reconstruction with catchment-based regression and LISA diagnostics, providing a replicable framework for subnational health systems assessment. Empirically, it generates fine-scale evidence on where maternal health and malaria prevention services fall short relative to need, offering actionable insights for targeted intervention. By explicitly linking population demand to service utilization, the study supports more equitable planning and resource allocation in pursuit of SDGs 3.1, 3.3, and 10.2.

2. Materials and Methods

2.1 Study area and spatial framework

This study adopts a catchment-based spatial epidemiological framework to examine maternal health service utilization and malaria prevention equity in Akwa Ibom State, Nigeria. Health facility catchment polygons constitute the primary unit of analysis and are hierarchically linked to wards, Local Government Areas (LGAs), and the state administrative structure. Analyses were conducted at the catchment level and subsequently aggregated to ward and LGA scales to support multilevel spatial interpretation.

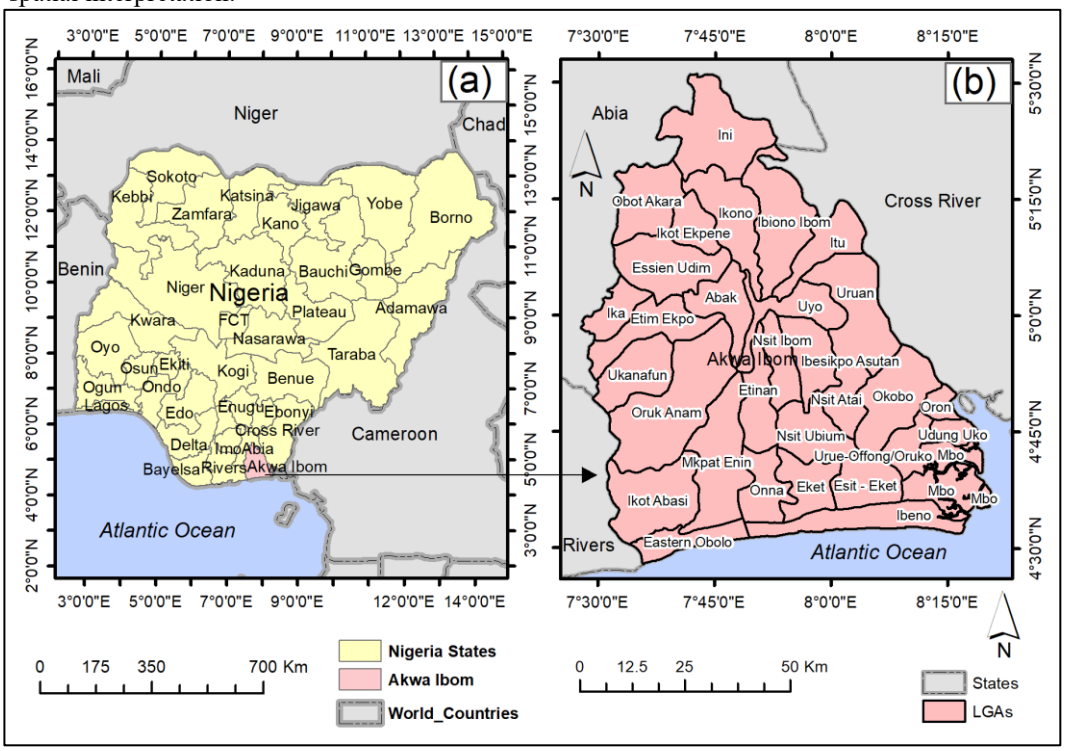


Figure 1 Study Area Map, subfigures (a) location of Akwa Ibom state in Nigeria, (b) LGAs in Akwa Ibom State.

2.2 Health service and Population data

Maternal health and malaria prevention service data for 2025 were obtained from the Nigeria District Health Information System 2 (DHIS2) platform (https://dhis2nigeria.org.ng). Extracted indicators included first antenatal care attendance ($ANC1_{2025}$) and uptake of intermittent preventive treatment in pregnancy ($IPTp3_{2025}$). These variables represent routine facility-reported counts of pregnant women receiving specific services during the study year.

Population denominators were derived from WorldPop (https://www.worldpop.org), which provides high-resolution gridded estimates of total population and age-specific cohorts. Catchment-

level population counts were obtained by spatially aggregating WorldPop raster layers to health facility catchment polygons. Key demographic variables included total population, women aged 15–45 years (women of reproductive age; WRA), and population aged 0–12 months.

2.2 Pregnancy estimation (2025)

Direct pregnancy counts are not routinely available in administrative health datasets. Therefore, annual pregnancies were estimated using a demographic reconstruction approach based on infant population data.

Let $P_{0-12m,2025}$ denote the catchment population aged 0–12 months in 2025 (WorldPop), used as a proxy for births occurring within a recent 12-month window around 2025. Annual live births were approximated by adjusting for infant survival to age one (S_1):

$$B_{2025} = \frac{P_{0-12m,2025}}{S_1} \qquad (1)$$

Total annual pregnancies were then estimated by inflating live births to account for pregnancy losses (miscarriage rate m and stillbirth rate s):

$$Preg_{2025} = B_{2025}(1 + m + s) = \left(\frac{P_{0-12m,2025}}{S_1}\right)(1 + m + s) \qquad (2)$$

To estimate the average number of women pregnant at any point during 2025 (pregnancy stock), annual pregnancies were multiplied by the gestational fraction, assuming a nine-month pregnancy duration:

$$Preg_{2025}^{stock} = Preg_{2025} \times \frac{9}{12} \qquad (3)$$

The following parameter values were applied uniformly across all catchments: infant survival probability $S_1 = 0.96$, miscarriage rate $m = 0.153$, and stillbirth rate $s = 0.0225$, yielding an overall inflation factor of $1 + m + s = 1.1755$.

2.3 Spatial disparities in antenatal care utilization

2.3.1 Indicator construction

To assess spatial disparities in antenatal care entry, first antenatal care attendance ($ANC1_{2025}$) was standardized against pregnancy burden. The primary utilization indicator was defined as:

$$ANC1_i^{Preg} = \frac{ANC1_i}{Preg_{2025,i}^{stock}} \times 100 \qquad (4)$$

Additional demand-adjusted indicators per 1,000 women of reproductive age and per 1,000 total population were computed for comparative analysis.

2.3.2 Demand–service modelling

To evaluate whether observed ANC utilization aligned with underlying population demand and spatial scale, a log-linear regression model was estimated:

$$\ln(ANC1_i + 1) = \alpha + \beta_1 \ln(WRA_i + 1) + \beta_2 \ln(Preg_{2025,i}^{stock} + 1) + \beta_3 \ln(Pop_i + 1) + \beta_4 \ln(Area_i + 1) + \varepsilon_i \qquad (5)$$

where $Area_i$ denotes catchment area (km²). Model residuals (ε_i) quantify deviations from expected ANC utilization given demographic pressure and spatial extent; negative residuals indicate potential under-utilization relative to demand.

2.3.3 Spatial autocorrelation and inequality assessment

Global spatial dependence in model residuals was assessed using Moran's I statistic. Where significant spatial autocorrelation was detected ($p < 0.05$), Local Indicators of Spatial Association (LISA) were computed to identify spatial clusters of under-coverage (Low–Low) and over-coverage (High–High). Inequality in ANC and IPTp3 coverage across catchments, wards, and LGAs was quantified using the Gini coefficient.

2.3.4 Software and reproducibility

All spatial processing and statistical analyses were implemented in R (version ≥ 4.5) using the `sf`, `spdep`, `classInt`, `ggplot2`, and `openxlsx` packages. The analytical workflow produced reproducible spatial datasets, statistical tables, and publication-ready maps.

3. Results

3.1 Demographic demand structure (2025)

3.1.1 Catchment coverage and population totals

The demographic analysis encompassed 654 health-facility catchments across Akwa Ibom State, covering a combined area of 6,858.86 km². Aggregated estimates indicate a total population of 6,453,997, including 1,454,361 women aged 15–45 years, 147,413 children aged 0–12 months, and 180,503 estimated pregnancies in 2025. The corresponding pregnancy stock, representing the average number of pregnant women present at any time during the year, was estimated at 135,378.

3.1.2 Distribution of children and pregnancy burden

Catchment-level estimates revealed pronounced spatial heterogeneity in maternal child demand. The number of children aged 0–12 months varied widely across catchments (mean 226, SD 190.83; median 177), with an interquartile range (IQR) of 105–275 and values spanning from 8.37 to 1,603 children per catchment (P90 = 440). Estimated annual pregnancies exhibited a similarly dispersed pattern (mean 276, SD 234; median 217; IQR 129–337; range 10–1,962). Pregnancy stock (PregSt_{25}) showed comparable variability, with a mean of 207.00 (SD 175.25), median 163, IQR 97–253, and range 8–1,472 (P90 = 404). As expected, infant counts and pregnancy measures were almost perfectly correlated (r ≈ 1.00), reflecting the deterministic conversion used in pregnancy estimation.

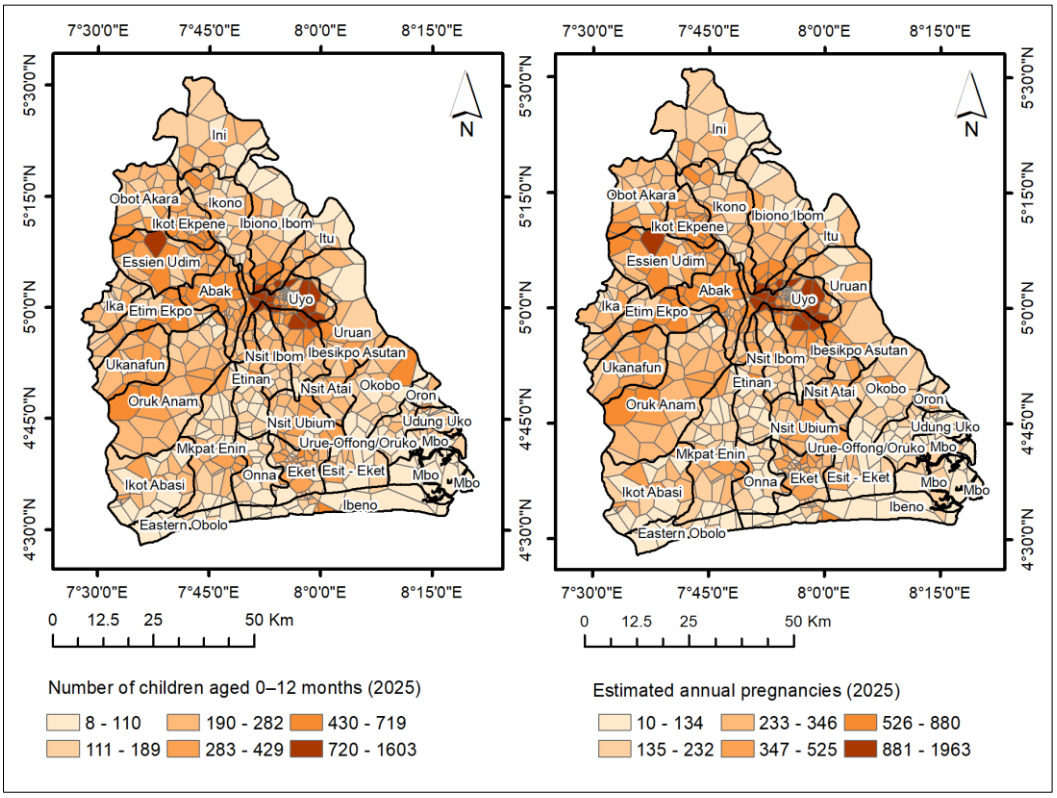


Figure 2 illustrates the demographic demand structure across catchments, showing a strong positive association between infants per 1,000 population and pregnancies per 1,000 women of reproductive age, thereby confirming the internal consistency of the pregnancy estimation framework.

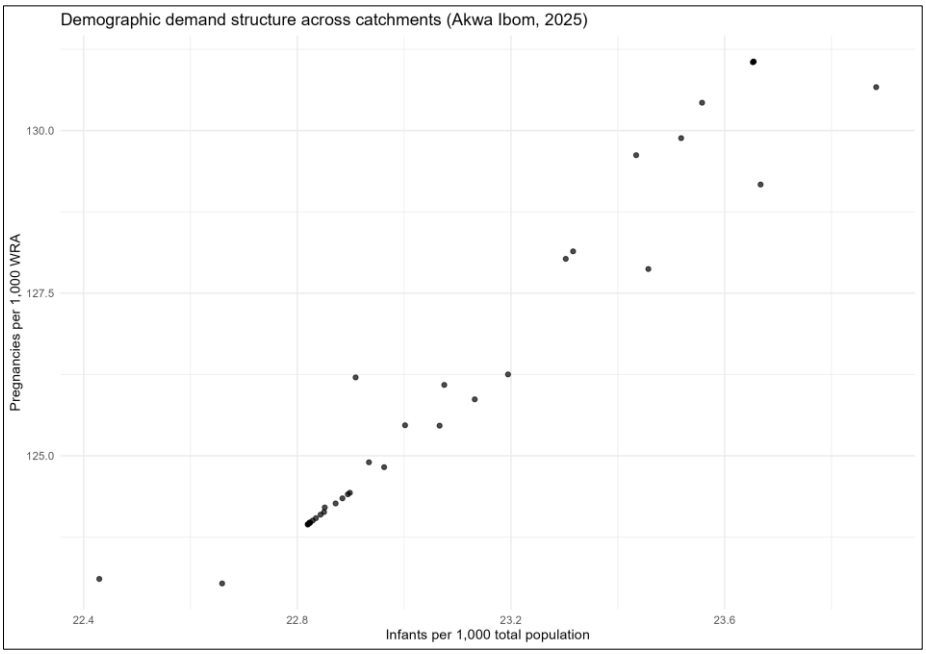


Figure 2. Demographic demand structure across health-facility catchments in Akwa Ibom State (2025).

3.1.3 Density patterns and concentration of demand

When standardized by catchment area, density measures remained highly variable. Infant density averaged 74 per km² (median 23, P90 286, maximum 454), while pregnancy density averaged 68 per km² (median 21, P90 263, maximum 556). At the state scale, aggregation substantially reduced apparent density, yielding 22 infants/km², 26 pregnancies/km², and 20 pregnant women/km², consistent with spatial averaging across heterogeneous catchments. In contrast, the infants-per-1,000-population indicator was relatively stable (mean 23 per 1,000, narrow range 22–24), reflecting a uniform age-structure ratio embedded in the gridded population model. Demographic burden was strongly concentrated, with the top 10% of catchments accounting for 29.62% of all infants, annual pregnancies, and pregnancy stock, underscoring the disproportionate concentration of maternal–child demand in a limited number of locations.

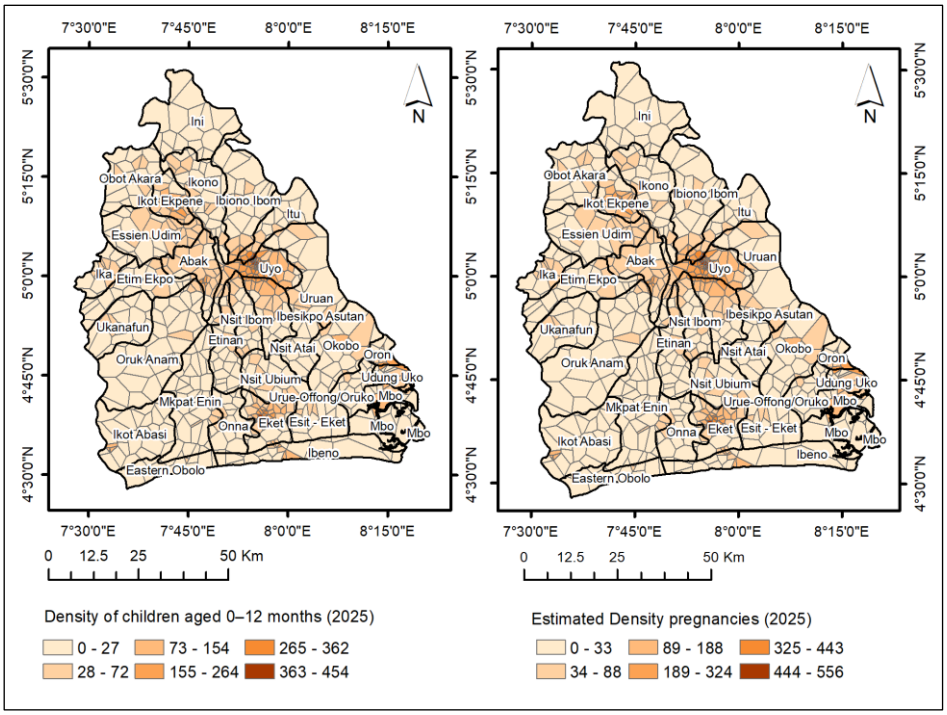


Figure 3. Density across health-facility catchments in Akwa Ibom State (2025).

3.1.4 LGA-level contrasts in demographic demand

Marked inter-LGA differences were observed in density-based demand indicators. Infant density ranged from approximately 4 per km² in the lowest-density LGAs to about 150 per km² in the highest-density LGAs, while pregnancy stock density varied from about 4 to 139 per km². Higher densities were concentrated in more urbanized LGAs (e.g., Uyo), whereas lower densities characterized less densely populated and coastal LGAs (e.g., Eastern Obolo). These contrasts highlight strong geographic gradients in maternal–child demand with direct implications for spatial targeting of antenatal and malaria prevention services.

3.1.5 Population-weighted demand distribution

Population-weighted quantiles provide a policy-relevant perspective on demand distribution. The weighted median catchment contained 290 infants, 355 estimated pregnancies, and 266 pregnant women (stock). The weighted upper quartile increased to 478 infants, 585 pregnancies, and 439 pregnant women, confirming that a substantial share of the population resides in catchments with markedly higher maternal–child demand than suggested by unweighted summaries.

3.2 Spatial patterns of antenatal care (ANC1) service intensity

3.2.1 ANC service intensity measures

Catchment-level antenatal care utilization exhibited pronounced spatial heterogeneity across Akwa Ibom State when standardized by alternative population-at-risk denominators. ANC1 intensity relative to pregnancy stock (ANC1 per 100 PregSt) ranged from 0.0 to values exceeding 1,200, indicating substantial variation in service utilization relative to concurrent pregnancy burden. Standardization by annual pregnancies (ANC1 per 100 Preg_{2025}) produced a similarly skewed distribution, while normalization by women of reproductive age (ANC1 per 1,000 WRA) revealed more moderate but still uneven patterns across catchments. Zero values were observed in several catchments despite non-zero pregnancy stock, highlighting localized gaps in ANC entry. Elevated values in selected catchments reflect concentrated service utilization and likely cross-boundary attendance, consistent with the functional openness of health facility catchments.

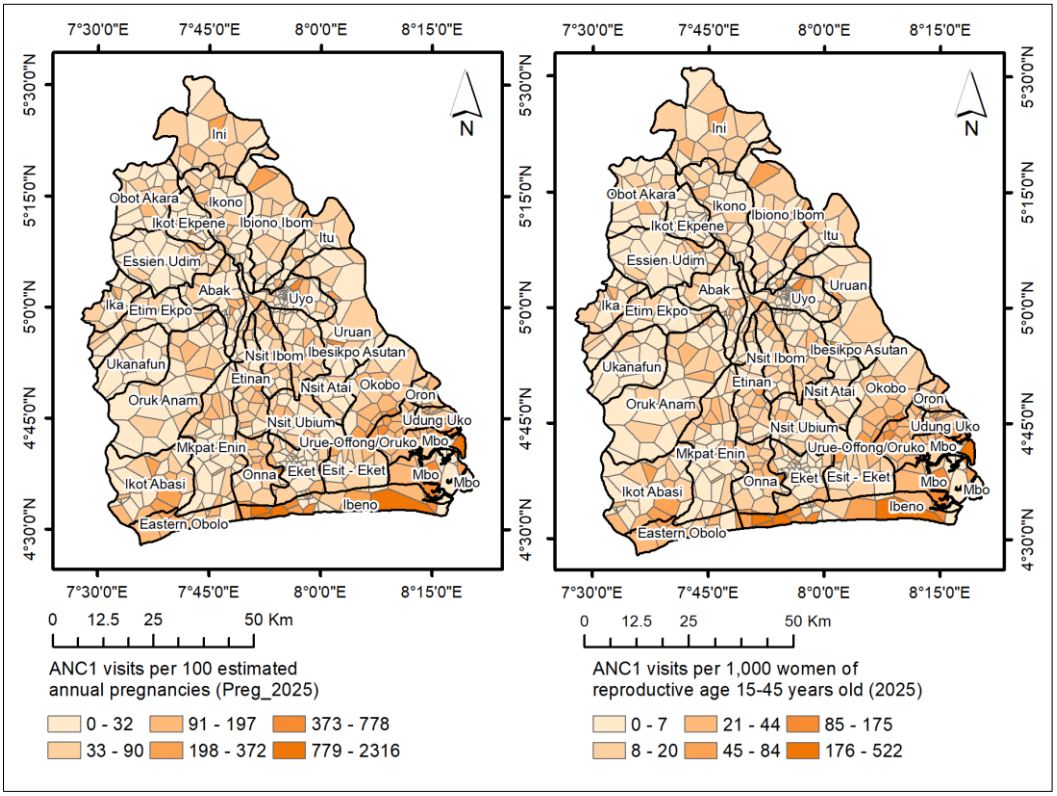
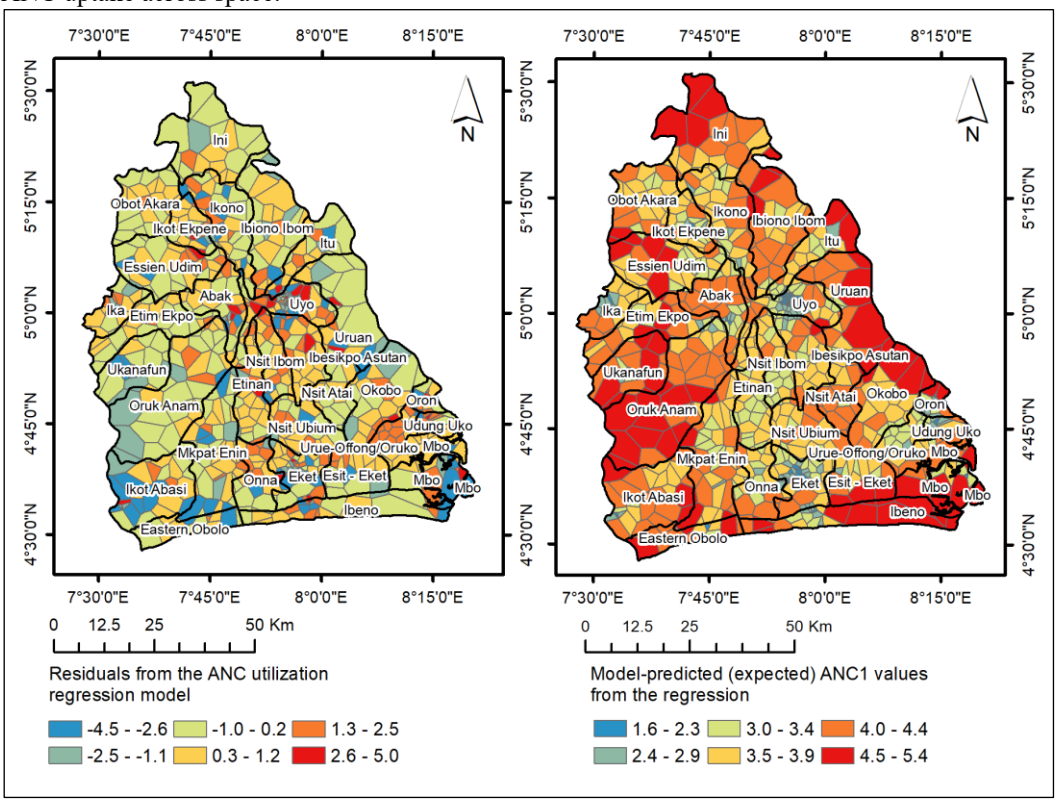


Figure 4. Catchment-level antenatal care utilization.

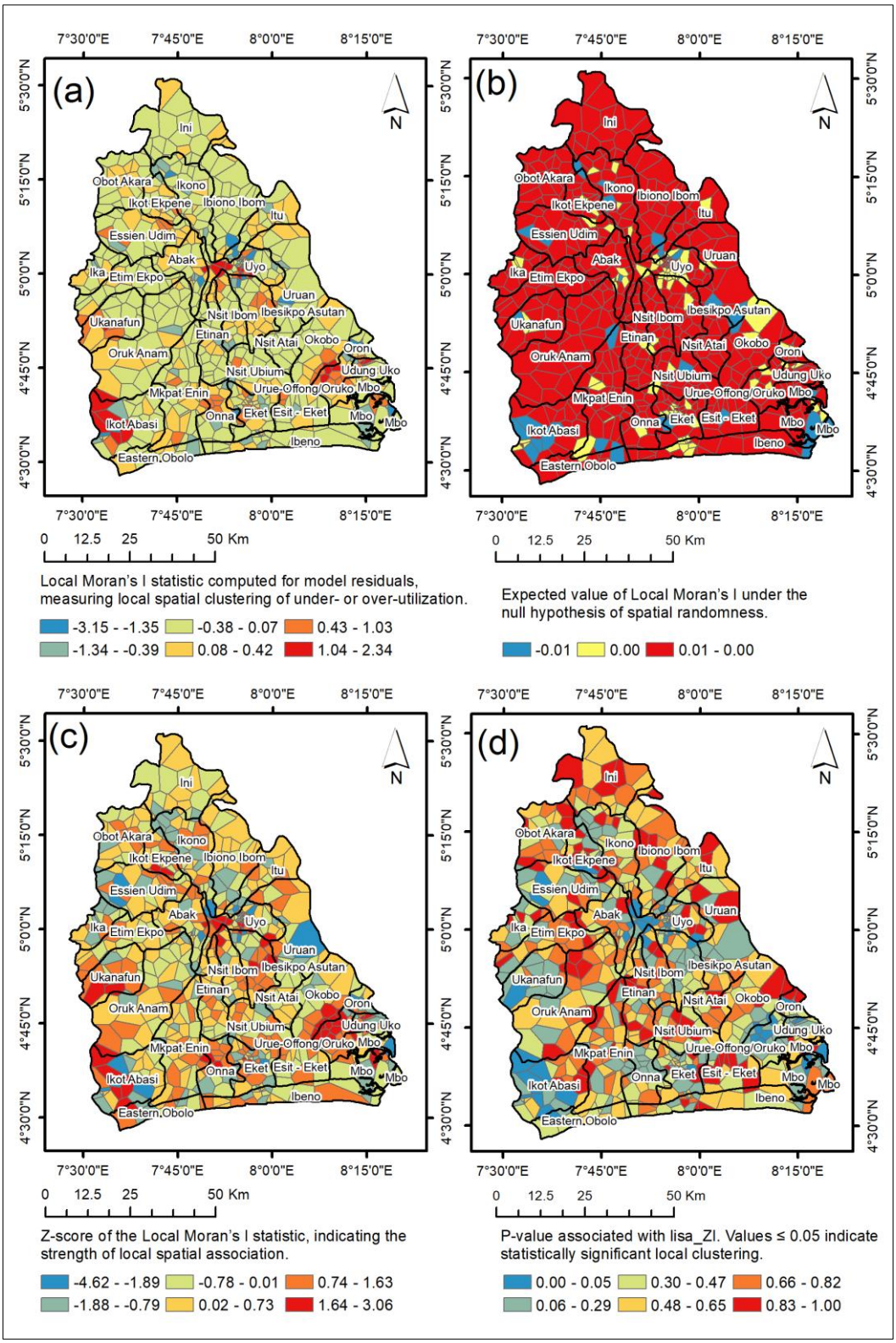
3.2.2 Regression diagnostics

The equity-adjusted regression model relating ANC1 attendance to demographic demand (women of reproductive age, pregnancy stock, total population) and spatial scale (catchment area) demonstrated a modest but statistically meaningful explanatory power. The model achieved an R^2 of 0.174 and an adjusted R^2 of 0.169, indicating that demographic structure accounts for a non-trivial share of observed spatial variation in ANC utilization. Residual diagnostics revealed substantial unexplained variability, suggesting that factors beyond population demand—such as facility functionality, service quality, accessibility, and care-seeking behavior—play an important role in shaping ANC uptake across space.



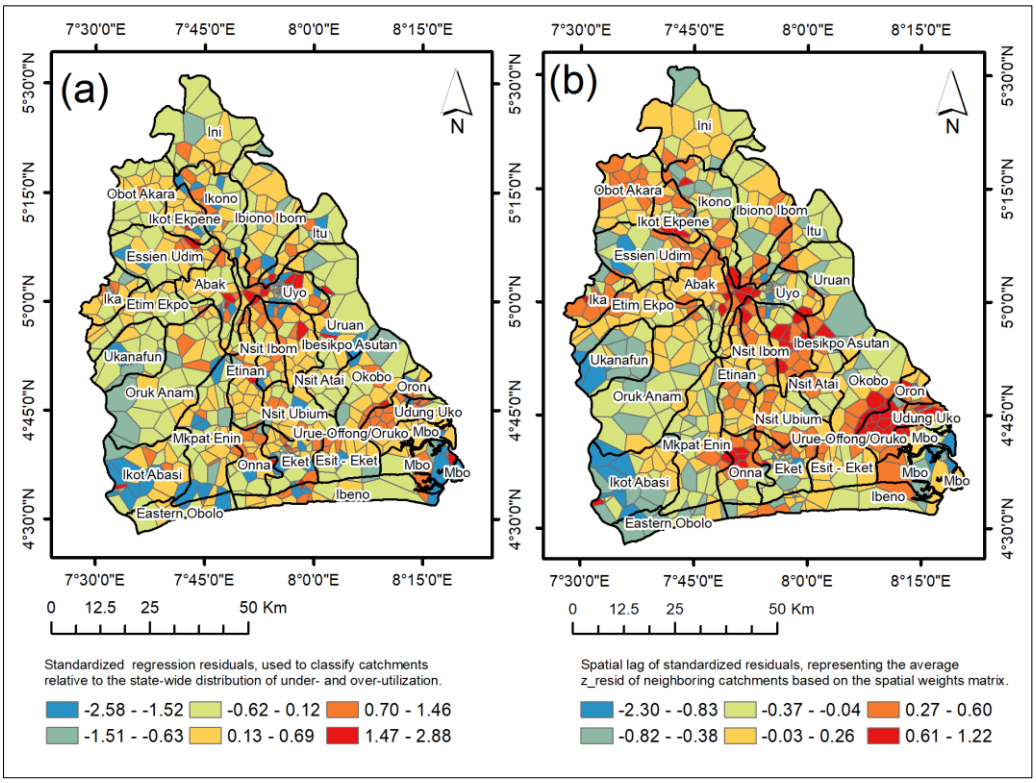
3.2.3 Local spatial autocorrelation (LISA) statistics

Global Moran's I applied to regression residuals under a queen contiguity spatial weights matrix indicated weak positive spatial autocorrelation ($I = 0.0339$), with a marginal level of statistical significance ($p = 0.064$). Although not significant at the conventional 5% threshold, this result suggests the presence of localized spatial structures in ANC under- and over-utilization that are not fully captured by demographic demand alone, warranting further investigation using local indicators of spatial association.



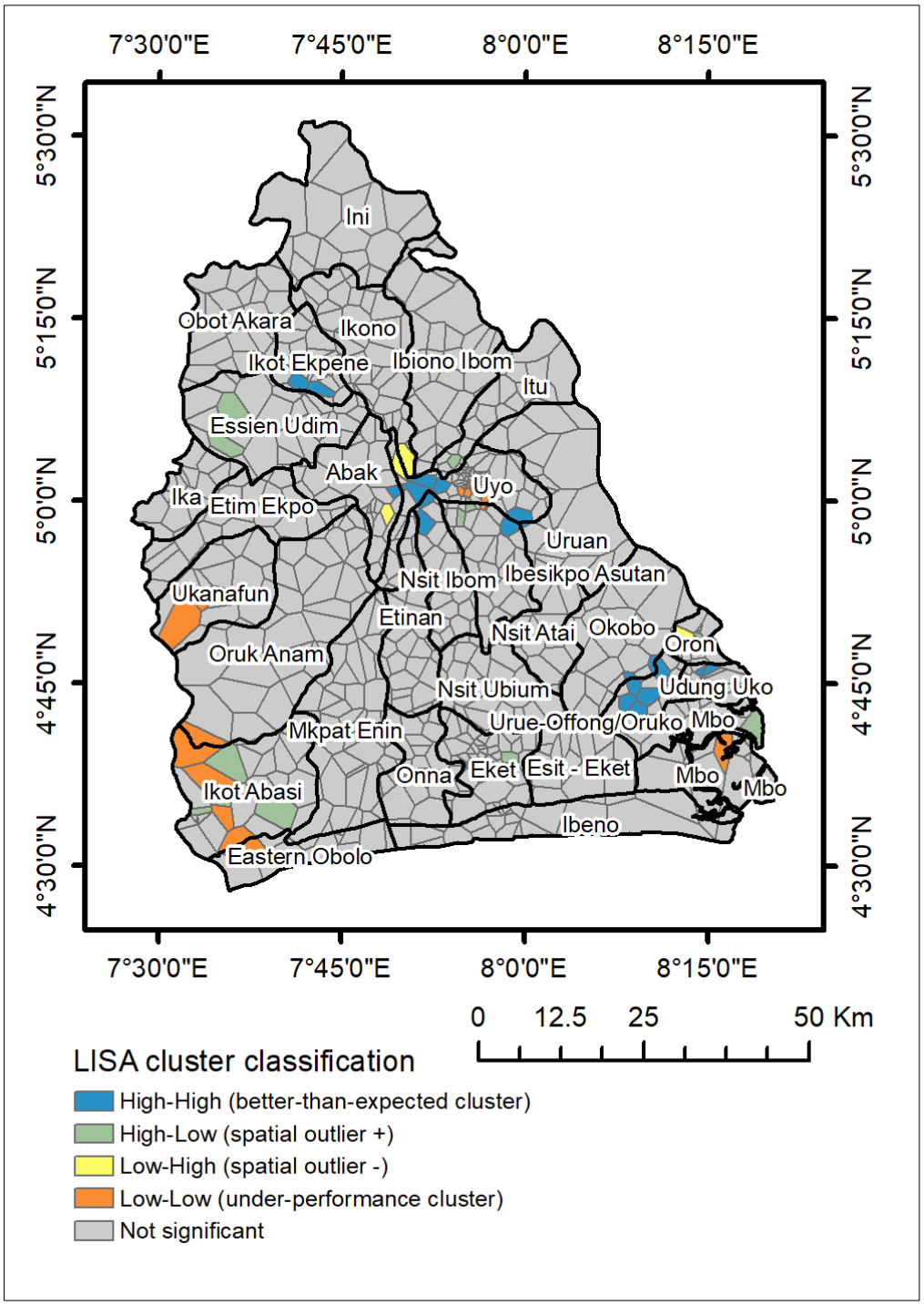
3.2.4 Standardized residuals and spatial lag

Standardized regression residuals (z-scores) revealed clear spatial contrasts in ANC performance relative to expected levels. Negative standardized residuals identified catchments with systematically lower-than-expected ANC utilization, whereas positive residuals indicated higher-than-expected utilization, potentially reflecting facility attractiveness or inflow from neighboring areas. The spatial lag of standardized residuals further demonstrated that under- and over-performance tended to occur in geographically proximate clusters, reinforcing the role of neighborhood effects in shaping ANC service utilization patterns.



3.2.5 LISA cluster classification

Local Moran's I classification identified distinct spatial patterns of ANC utilization relative to demographic demand. Low–Low clusters—representing contiguous catchments with persistently low ANC utilization relative to expected levels—were observed in multiple locations, highlighting geographically concentrated pockets of under-service. High–High clusters indicated areas of consistently strong ANC performance surrounded by similarly high-performing neighbors. Additional High–Low and Low–High spatial outliers revealed localized anomalies where individual catchments deviated sharply from surrounding conditions. The majority of catchments showed no statistically significant local spatial association, indicating that while clustering exists, inequities are highly localized rather than uniformly regional.



4. Discussion

4.1 Interpretation of demographic demand patterns

This study provides a fine-scale, catchment-based quantification of maternal–child demographic demand in Akwa Ibom State, revealing substantial spatial heterogeneity that is largely obscured in conventional LGA- or state-level summaries. The strong concentration of infants, estimated pregnancies, and pregnancy stock within a limited subset of catchments underscores the inherently uneven spatial distribution of reproductive health demand. Similar concentration patterns have been reported in recent spatial demographic analyses, which emphasize that population demand for maternal services is rarely spatially uniform, even within relatively small administrative units (Leasure et al., 2022; Sorichetta et al., 2023).

The stability observed in infants per 1,000 population across catchments, contrasted with wide variability in absolute counts and density measures, reflects the demographic regularization embedded in gridded population models. While this consistency supports the internal validity of the pregnancy reconstruction framework, it also highlights the importance of absolute and density-based indicators for operational health planning, where service demand is driven by numbers rather than ratios alone (Leasure et al., 2022).

4.2 ANC service intensity relative to demographic demand

By standardizing ANC1 attendance against pregnancy stock, annual pregnancies, and women of reproductive age, this study demonstrates pronounced spatial inequities in antenatal care entry across Akwa Ibom State. Extremely high ANC1-to-pregnancy ratios observed in selected catchments likely reflect cross-boundary service utilization, where facilities attract pregnant women from surrounding catchments. Such patterns are increasingly recognized in facility-based health systems and challenge the assumption that catchment populations are closed systems (Joseph et al., 2021; Wiens et al., 2023).

Conversely, the presence of zero or very low ANC1 intensity in catchments with non-negligible pregnancy stock suggests localized barriers to service access or utilization. Recent studies emphasize that geographic proximity alone does not guarantee service uptake, as sociocultural factors, facility readiness, and perceived quality strongly mediate care-seeking behavior (Adedokun et al., 2022; Kruk et al., 2023). The results therefore reinforce the need to interpret ANC utilization metrics within a spatially explicit demand framework rather than as raw service counts.

4.3 Insights from demand-adjusted regression modelling

The log-linear demand–service model explained a modest but meaningful proportion of the spatial variation in ANC utilization. While the adjusted R^2 indicates that demographic structure and catchment size alone cannot fully account for observed patterns, this result is consistent with recent health-services research demonstrating that utilization outcomes are shaped by a complex interplay of supply-side and demand-side factors (Leslie et al., 2021; Barasa et al., 2022).

Importantly, the residuals derived from the model serve as an interpretable equity metric, capturing deviations between observed ANC attendance and expected levels given population pressure. This residual-based approach has gained traction in recent spatial health equity studies, as it allows the identification of under-performing areas without conflating low utilization with low demand (Joseph et al., 2021; Wiens et al., 2023).

4.4 Spatial dependence and localized inequities

Global Moran's I analysis revealed weak but positive spatial autocorrelation in ANC utilization residuals. Although marginally non-significant at the 5% level, the magnitude and direction of the statistic are consistent with recent evidence that maternal health service inequities often manifest as localized clusters rather than broad regional gradients (Kang et al., 2022; Jia et al., 2023).

Local Indicators of Spatial Association further clarified this pattern by identifying discrete Low–Low clusters of under-utilization, as well as High–High clusters of consistently strong performance. These findings align with emerging literature showing that health system performance is frequently shaped by neighborhood-level effects, such as shared infrastructure constraints, referral dynamics, and common socioeconomic contexts (Wang et al., 2022; Kang et al., 2022). The predominance of non-significant areas suggests that inequities are spatially fragmented, reinforcing the importance of localized interventions rather than blanket policy responses.

4.5 Implications for malaria prevention and integrated maternal health planning

The methodological framework and findings have direct relevance for malaria prevention strategies targeting pregnant women. Catchments exhibiting low ANC entry relative to pregnancy burden are likely to experience parallel gaps in IPTp3 uptake, given the reliance of malaria prevention delivery on antenatal platforms. Recent evidence highlights that missed ANC contacts remain

a critical bottleneck in achieving equitable IPTp coverage, even in settings with adequate commodity availability (Rogerson et al., 2022; Hill et al., 2023).

By explicitly linking demographic demand, ANC utilization, and spatial clustering, this study provides a replicable approach for identifying priority areas where integrated maternal and malaria services can yield the greatest marginal gains. Such spatially targeted strategies are increasingly advocated as essential for accelerating progress toward SDG 3 in heterogeneous health systems (WHO, 2023; Hill et al., 2023).

4.6 Strengths, limitations, and future research

A major strength of this study lies in its integration of high-resolution demographic data with routine health information within a coherent catchment-based spatial framework. However, several limitations warrant consideration. First, pregnancy estimates rely on demographic reconstruction rather than direct measurement, introducing uncertainty that may vary across settings. Second, facility-level quality, staffing, and commodity availability were not explicitly modelled, despite their known influence on service utilization. Third, the open nature of catchment boundaries complicates strict attribution of service use to resident populations.

Future research could address these limitations by incorporating facility readiness indicators, travel-time accessibility, and longitudinal service data to capture temporal dynamics. Extending this framework to other Nigerian states would further support comparative analyses and evidence-based prioritization under national maternal and malaria control strategies.

Supplementary Materials: Available at https://github.com/zubairgis/nigeria-hensard

Data Availability Statement: The satellite data used in this study are open to access as follows:

Administrative: https://developers.google.com/earth-engine/datasets/catalog/ FAO/GAUL/2015/level2
Health Data: https://dhis2nigeria.org.ng/dhis/dhis-web-dashboard/#/

Author Contributions: Conceptualization, Z.I. and Y.J.C.; methodology, Z.I. F.M. and U.U.E.; formal analysis, Z.I., Y.J.C., and R.K.H.; investigation, USN, U.U.E., Y.J.D., F.M. and R.K.H.; data curation, U.U.E. and E.L.E.; writing original draft preparation, Z.I. USN and Y.J.C.; writing—review and editing, U.U.E., E.L.E., and R.K.H.; supervision, Z.I.; project administration, Z.I. F.M.and Y.J.C. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	
ANC	Antenatal Care
ANC1	First Antenatal Care Visit
ANCA	Total Antenatal Care Attendance
IPTp	Intermittent Preventive Treatment in pregnancy
IPTp3 (IPT3)	Third dose of Intermittent Preventive Treatment in pregnancy
IPT1	First dose of Intermittent Preventive Treatment

LGA	Local Government Area
LISA	Local Indicators of Spatial Association
MiP	Malaria in Pregnancy
DHIS2	District Health Information Software, version 2

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