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Geospatial Disparities in Immunization Coverage: Identifying High Zero-Dose Wards for Targeted Primary Healthcare Intervention in Hard-to-reach Settings

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Abstract

Background: Achieving equitable childhood immunization remains a major primary healthcare challenge, particularly in geographically isolated and hard-to-reach populations. In Bayelsa State, Nigeria, difficult riverine terrain, limitations in cold-chain infrastructure, health workforce constraints, and dispersed settlements contribute to persistent gaps in routine immunization. Aggregate coverage indicators may conceal substantial subnational inequities and limit the efficient deployment of nurses, community health workers, vaccines, outreach teams, and other primary healthcare resources. This study assessed geospatial disparities in immunization coverage and identified high-burden zero-dose wards requiring targeted intervention.

Methods: A retrospective descriptive analysis of 2025–2026 routine immunization administrative data was conducted across all 8 Local Government Areas (LGAs) and 105 wards, representing a target population of 107,108 children under one year. Penta1 coverage, number of zero-dose children, zero-dose prevalence, and coverage gaps relative to the 90% benchmark were determined. Geographic inequalities were assessed using absolute range, top-10/bottom-10 ratio, Gini coefficient, Lorenz curve, and Pareto 80/20 analysis. A composite risk approach incorporating prevalence, absolute burden, and coverage gap was used to classify wards as CRITICAL, HIGH, MODERATE, or LOW priority. Schematic choropleth and ward-level bubble maps were used for operational visualization.

Results: Overall Penta1 coverage was 68.8%, corresponding to a zero-dose prevalence of 31.2%. Considerable geographic inequality was observed. LGA-level zero-dose prevalence ranged from 8.5% in Ekeremor to 61.8% in Southern Ijaw, representing a 53.3-percentage-point range and a top-10/bottom-10 ratio of 7.3. Ward-level disparities were more pronounced, with zero-dose prevalence ranging from 0% to 83.5%. The Gini coefficient of 0.27 demonstrated moderate inequality in the distribution of the zero-dose burden. Pareto analysis showed that only 15 of the 105 wards (14.3%) accounted for 80% of the total zero-dose burden, with 11 classified as CRITICAL priority. Southern Ijaw alone contributed 42% of the total burden. Newly identified peripheral settlements also accounted for more than 3,000 zero-dose children previously omitted from routine microplans.

Conclusion: Zero-dose children were highly concentrated within a relatively small number of geographic areas, demonstrating that aggregate LGA-level indicators can mask substantial ward-level inequities. Targeting the 15 wards responsible for 80% of the zero-dose burden may provide a more efficient and equitable approach than uniformly distributing interventions across entire LGAs. For nursing and primary healthcare practice, the findings support differentiated deployment of frontline health workers, intensified outreach and mobile services, strengthened defaulter tracking, community engagement, reliable cold-chain support, and dedicated transport arrangements for riverine populations. Integrating ward-level equity metrics, geospatial visualization, and risk-based prioritization into routine primary healthcare planning could strengthen evidence-based resource allocation and accelerate progress toward universal immunization coverage.

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Keywords: Zero-dose children; Immunization equity; Geospatial disparities; Primary healthcare; Gini coefficient; Pareto analysis; Hard-to-reach populations; Routine immunization; Health equity

Introduction

Zero-dose children are operationally defined as children who do not receive a single dose of diphtheria, tetanus and pertussis-containing vaccine (DTP/Penta), or more broadly as children who have not received any routine immunisations, including the first dose of DTP [1,2]. According to WHO/UNICEF 2024 coverage estimates released in 2025, about 14.3 million infants worldwide were zero-dose—meaning they received no routine vaccines in their first year of life [3]. Globally, the number was 14.3 million children in 2024. Zero-dose children are disproportionately found in settings affected by fragility, conflict or humanitarian crises, and in marginalized communities, conflict zones, vaccine-hesitant households, and areas with limited or fragile healthcare infrastructure. Gavi, the Vaccine Alliance, has made reaching zero-dose children its key priority for the next five years, with the goal to reduce the number of zero-dose children by 25% by 2025, and by 50% by 2030, which will also mark the closing of the Sustainable Development Goals [4]. Nigeria is estimated to have over 2.2 million zero-dose children, accounting for 16% of the global total, making it the country with the highest number of unimmunized [3]. UNICEF reports about 2.2 million Nigerian children do not receive a single dose of any vaccine every year, making Nigeria the country with second highest number of zero-dose children in the world. Other estimates show in 2022, there were an estimated 2.3 million zero-dose children in Nigeria, the second largest population globally, and based on global estimates from WHO/UNICEF in 2022, Nigeria has the highest number of zero-dose children, with >2.3 million unvaccinated [1]. According to the 2021 Multiple Indicator Cluster Survey / National Immunization Coverage Survey (MICS/NICS), 70% of children aged 12-23 months had received the first dose of pentavalent vaccine, or Penta1, while only 36% of children aged 12–23 months have received all recommended immunizations, while 18% received none. Only about 57% of eligible children in Nigeria were fully vaccinated as of 2021 [5]. Factors driving zero-dose persistence include insecurity, poor access to healthcare, vaccine hesitancy, lack of trust in vaccine efficacy, behavioural and gender-related barriers and financing problems. UNICEF's State of the World's Children 2023 report highlights that children from the poorest households in the bottom 10% are less likely to be immunized than those in wealthiest 10%, with 67 million children missing out on routine immunizations between 2019-2021 globally. Recent evidence shows spatial clustering of zero-dose children aged 12 to 59 months across 33 countries in sub-Saharan Africa. High-resolution geospatial mapping following Nigeria's 2021 MICS/NICS has been employed to determine prevalence and predict risk areas. Upon release of MICS/NICS 2021, triangulation led to re-prioritization that identified 100 LGAs as having high number of zero-doses for focused intervention, and Nigeria's Zero-Dose Learning Hub has documented operational plans to reduce zero-dose in priority LGAs [4]. Bayelsa is a riverine state in South-South Nigeria with difficult terrain where 70% of communities are accessible only by boat. Routine administrative data suggest low Penta1 coverage, but LGA and ward-level heterogeneity is masked by state aggregates. While national geospatial models exist, ward-level analysis using routine data for targeted microplanning is limited in Bayelsa. Identifying high zero-dose wards using Pareto 80/20 and inequality metrics (Gini, Lorenz) can enable efficiency gains, as health workers are already reaching zero-dose children in Nigeria's urban slums, but similar riverine strategies are underexplored.

Statement of the Problem

Zero-dose children, defined as those who fail to receive a single dose of pentavalent vaccine (Penta1), represent the most extreme form of immunization inequity and a marker of populations completely missed by health systems. Globally, 14.3 million children remain zero-dose, with Nigeria accounting for over 2.2 million — the second highest burden worldwide. In Bayelsa State, zero-dose is not a recent emergency created by COVID-19 disruptions, but a chronic, entrenched problem that predates the global and national Big Catch-Up initiatives. For over a decade, routine administrative data and national surveys have consistently reported low Penta1 coverage in Bayelsa, typically below 70%, far short of the WHO 90% benchmark. NDHS 2018 and MICS/NICS 2021 both placed Bayelsa among low-performing states in South-South Nigeria, with a significant proportion of children receiving no routine vaccines [5,6]. This indicates stagnation rather than sudden deterioration — a persistent failure of routine systems to reach all children. The Big Catch-Up strategy was launched globally in 2023 and in Nigeria in 2024 to reach children missed between 2019-2022 and restore coverage to pre-pandemic levels [7,8]. However, its implementation in Bayelsa was confronted with a fundamental operational challenge: there was no ward-level empirical evidence on where zero-dose children are concentrated. Existing microplans and resource allocation for routine immunization and for Big Catch-Up have been based on LGA aggregates and modelled estimates from MICS/NICS, which mask substantial intra-LGA and inter-ward heterogeneity. In a riverine state where 70% of communities are accessible only by boat, with sparse health facilities, low cold chain functionality, limited health workforce, and high transportation costs, assuming uniform distribution of zero-dose across 105 wards leads to inefficient use of scarce resources. Field reports and program data suggest marked

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geospatial disparities: riverine wards in Southern Ijaw, Brass, and Ekeremor and urban slum wards in Yenagoa consistently report low coverage and repeated vaccine stock-outs, missed outreach sessions due to lack of boats, and high numbers of unimmunized children, while upland wards in Sagbama and Kolokuma/Opokuma perform relatively better. Yet, without systematic quantification using inequality metrics such as range, ratio, Gini coefficient, Lorenz curve, and Pareto analysis, and without geospatial visualization through choropleth and bubble mapping, these disparities remain anecdotal and could not inform prioritization. The absence of ward-level prioritization has practical consequences. Uniform statewide campaigns — integrated campaigns, outreach days, and routine fixed sessions distributed equally — were not impactful. Health workers spend disproportionate time in transit to low-burden riverine settlements while high-burden wards receive only monthly outreach instead of required multiple weekly contacts. This inefficiency undermines progress toward Immunization Agenda 2030 and Gavi 5.0 target of 50% reduction in zero-dose by 2030 [9]. Therefore, the core problem this study intend to addresses is that Bayelsa State has a historically high and geographically inequitable zero-dose burden that predates Big Catch-Up, but lacks ward-level empirical evidence and geospatial prioritization tools to guide targeted, efficient intervention and to provide a baseline for evaluating Big Catch-Up impact.

Justification of the Study

1. ***Provides Baseline Empirical Evidence for Big Catch-Up Evaluation:*** Big Catch-Up implementation (2024-2028) requires a pre-intervention baseline to measure progress. Currently, Bayelsa has no ward-level baseline built from routine administrative data at inception of Big Catch-Up. Conducting research to generate such empirical evidence is essential to enable the State Primary Health Care Board to measure whether Big Catch-Up actually reduces zero-dose by comparing future endline data to a documented baseline. Without this, evaluation is impossible.

2. ***Shifts from Uniform to Targeted Efficient Strategy***: Global evidence shows that when burden is concentrated, targeted geographic approaches are more efficient than uniform campaigns. Empirical research is needed to test whether Pareto 80/20 principle applies in Bayelsa — whether a small proportion of wards holds majority of zero-dose burden. If proven, this provides justification to shift resources to high-burden clusters, saving boat hiring costs, health worker time, and cold chain resources in a state with severe funding constraints.

3. ***Addresses Riverine Geospatial Inequity***: Bayelsa's riverine terrain creates unique access barriers not captured in national models. Research that quantifies geospatial clustering — whether high zero-dose wards cluster in southern riverine belt and urban slums — provides evidence for differentiated strategies: boat-based mobile teams for riverine versus evening/weekend clinics and private sector linkage for urban slums, rather than one-size-fits-all approach.

4. ***Policy and Programmatic Relevance***: The State Annual Operational Plan, State Immunization Emergency Operation Centre microplanning, and Gavi Health System Strengthening proposals all require ward-level prioritization. This research provide a prioritization matrix (CRITICAL/HIGH/MODERATE/LOW) and a ward action plan as actionable tools for LGA teams, directly informing resource allocation and operational planning.

5. ***Contribution to Knowledge***: No published study has analyzed ward-level zero-dose disparities in Bayelsa using inequality metrics (Gini, Lorenz, Pareto) and geospatial mapping. Existing literature focuses on national or LGA-level modelling. This study filled the gap in sub-national operational research and provide replicable methodology for other riverine states in Niger-Delta Region (Delta, Rivers, Akwa Ibom, Cross River).

6. ***Public Health Significance***: Each zero-dose child is at risk of vaccine-preventable diseases including diphtheria, pertussis, measles, and polio. Bayelsa has recorded diphtheria outbreaks and persistent cVDPV2 transmission linked to immunity gaps. Empirical evidence to target zero-dose is therefore critical to prevent outbreaks, reduce under-five mortality, and improve community immunity.

In summary, this research is justified because zero-dose is a chronic pre-existing problem in Bayelsa with high hard-to-reach burden that was not resolved by previous strategies, and Big Catch-Up is being implemented without ward-level empirical evidence on where zero-dose children are. Generating such evidence through geospatial disparity analysis is necessary to ensure Big Catch-Up does not repeat historical failures of uniform approaches and to provide a measurable baseline for future evaluation.

General Objective

To determine the geospatial disparities in Penta1 immunization coverage and identify high zero-dose wards in Bayelsa State for targeted intervention.

Specific Objectives

1. To determine the distribution of Penta1 immunization coverage and zero-dose prevalence across Local Government Areas (LGAs) and wards in Bayelsa State.

2. To quantify geospatial disparities in zero-dose burden across wards in Bayelsa State using inequality metrics including range, top/bottom ratio, Gini coefficient, Lorenz curve, and Pareto 80/20 analysis.

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3. To visualize the geospatial distribution of zero-dose prevalence and burden at LGA and ward levels using choropleth maps and bubble maps to identify clustering of high-burden areas.
4. To develop and apply a prioritization matrix to classify wards into priority categories (CRITICAL, HIGH, MODERATE, LOW) based on absolute zero-dose number and zero-dose prevalence for targeted intervention.
5. To develop a ward-level action plan with tailored intervention strategies for each priority category to guide efficient resource allocation and microplanning for zero-dose reduction in Bayelsa State.

Research Questions

Main Research Question:

What are the geospatial disparities in Penta1 immunization coverage and which wards are high zero-dose wards requiring targeted intervention in Bayelsa State?

Specific Research Questions:

RQ1: What was the distribution of Penta1 immunization coverage and zero-dose prevalence across LGAs and wards in Bayelsa State?

RQ2: What was the extent of geospatial disparity in zero-dose burden across wards in Bayelsa State when measured using range, top10/bottom10 ratio, Gini coefficient, Lorenz curve, and Pareto 80/20 analysis?

RQ3: What was the geospatial pattern of zero-dose prevalence and burden at LGA and ward levels, and do high zero-dose wards cluster geographically?

RQ4: How could wards in Bayelsa State be classified into priority categories (CRITICAL, HIGH, MODERATE, LOW) based on absolute zero-dose number and zero-dose prevalence?

RQ5: What tailored intervention strategies were appropriate for each ward priority category to ensure efficient resource allocation and microplanning for zero-dose reduction in Bayelsa State?

Research Hypotheses

Disparity Hypothesis

H0 - Null Hypothesis: There is no significant geospatial disparity in zero-dose prevalence across wards in Bayelsa State. The distribution of zero-dose children is uniform across wards (Gini coefficient = 0, top10/bottom10 ratio = 1).

H1 - Alternative Hypothesis: There is significant geospatial disparity in zero-dose prevalence across wards in Bayelsa State. The distribution is inequitable (Gini coefficient > 0.25, top10/bottom10 ratio > 2, wide range).

Pareto Hypothesis

H0: Zero-dose burden is not concentrated; 80% of zero-dose children are not contained within 20% of wards (Pareto 80/20 does not apply).

H1: Zero-dose burden is concentrated; 80% of zero-dose children are contained within approximately 20% or fewer wards (Pareto principle applies), indicating that targeting few wards can achieve majority reduction.

Geospatial clustering Hypothesis

H0: There is no geospatial clustering of high zero-dose wards in Bayelsa State. High-burden wards are randomly distributed.

H1: There is significant geospatial clustering of high zero-dose wards in Bayelsa State. High-burden wards cluster in specific geographic belts (e.g., southern riverine LGAs and Yenagoa urban slums), indicating shared access barriers.

Scope and Limitation of the Study

Scope of the Study

Geographical Scope: This study was limited to Bayelsa State, South-South Nigeria, comprising eight Local Government Areas: Brass, Ekeremor, Kolokuma/Opokuma, Nembe, Ogbia, Sagbama, Southern Ijaw, and Yenagoa. The state was purposively selected due to its riverine terrain, historically low immunization coverage, and documented challenges in reaching riverine and urban slum populations. Within the state, the unit of analysis was the ward (n=105), which was the operational microplanning unit for routine immunization in Nigeria. Geospatial analysis was limited to LGA and ward levels; community and settlement levels were not included due to lack of geocoded settlement-level data.

Content Scope: The study focused exclusively on zero-dose children, operationally defined as children who had not received the first dose of pentavalent vaccine (Penta1), which was a standard proxy for zero-dose. The study did not assess full immunization coverage, dropout rates between Penta1-Penta3, or other antigens (BCG, measles, yellow fever). Variables are limited to those available in routine administrative data: target population (<1 year), number immunized with Penta1, zero-dose derived (target minus immunized), and catch-up immunization data where available. Inequality was assessed using range, top/bottom ratio, Gini coefficient, Lorenz curve, and Pareto 80/20 analysis. Geospatial distribution was visualized using schematic choropleth maps at LGA level and bubble maps at ward level.

Temporal Scope: The study focused on the period preceding and at inception of the Nigeria Big Catch-Up Plan (2024-2028), covering routine immunization performance in the years prior to Big Catch-Up. This period was critical

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because it represents the baseline upon which Big Catch-Up aims to improve. It provides baseline empirical evidence for future evaluation.

Methodological Scope: This was a descriptive cross-sectional study using secondary analysis of routine administrative data from the Bayelsa State Primary Health Care Board and Primary Health Centres in Bayelsa State. Analysis was limited to quantitative methods; qualitative exploration of reasons for zero-dose (such as vaccine hesitancy, gender barriers, health worker attitudes) is outside the scope but recommended for future research.

Limitation of the Study

Use of Administrative Data and Target Population Estimation: The study relies on routine administrative data where target population is projected from 2006 census with assumed growth rates, which might overestimate or underestimate true infant population in wards, especially in rapidly urbanizing Yenagoa and in riverine wards with out-migration. This was a common limitation in Nigeria's routine immunization data and might affect absolute zero-dose numbers and prevalence estimates. However, this was the same data used by the state for program planning, so findings remain operationally relevant.

Schematic Maps, Not GPS-Based Geospatial Analysis: Geospatial visualization in this study uses schematic choropleth and bubble maps based on relative LGA and ward positions, not precise GPS coordinates of health facilities or settlements. Bayelsa lacks complete geocoded settlement lists and health facility coordinates for all 105 wards. While this limits precise distance-to-facility analysis, the schematic maps still demonstrate clustering and are sufficient for operational prioritization. Future studies should integrate GPS coordinates for facility and settlement mapping.

No Individual-Level Socio-Demographic Data: Routine administrative data was aggregate and did not include individual-level factors such as maternal education, household wealth, distance to facility, or reasons for non-vaccination. Therefore, this study cannot explain why zero-dose was high in certain wards, only where and how much disparity exists. Determinants analysis requires household surveys such as MICS/NICS or qualitative research.

Potential Data Quality Issues: Administrative immunization data might be affected by over-reporting or under-reporting, incomplete reporting from private facilities (which provide 15-20% of immunization in Yenagoa), and delays in reporting from riverine wards. Data validation through triangulation with survey data (MICS/NICS, NDHS) was not within the scope but is recommended.

Cross-Sectional Design — No Causality: As a cross-sectional analysis, the study describes distribution and disparities at one point in time but could not establish causality or trends over time. It could not determine whether disparities were increasing or decreasing, nor could it attribute zero-dose to specific health system failures. Longitudinal trend analysis is recommended for future research.

Limited Generalizability Beyond Bayelsa: Findings are specific to Bayelsa's riverine and urban slum context and might not be generalizable to highland states with different terrain and population density. However, methodology (Pareto, Gini, prioritization matrix) is replicable and can be adapted to other states, particularly other Niger Delta riverine states.

No Assessment of Catch-Up Strategies and Defaulter Tracking Effectiveness: The study identifies high zero-dose wards but does not evaluate the effectiveness of existing defaulter tracking, outreach sessions, or catch-up strategies. Intervention effectiveness should be assessed in implementation research following this prioritization.

Mitigation: Despite these limitations, the study used standard WHO definitions, applies multiple inequality metrics for triangulation, and uses operational data actually used by program managers, making findings highly relevant for decision-making. Limitations are acknowledged and do not invalidate the core findings that zero-dose burden is geographically concentrated and requires targeted intervention.

Literature Review

The concept of zero-dose children has gained global prominence under the Immunization Agenda 2030 (IA2030) [9]. According to the World Health Organization (WHO) and Gavi, the Vaccine Alliance, zero-dose children are defined as children who have not received the first dose of diphtheria, tetanus and pertussis-containing vaccine (DTP1), which in most countries including Nigeria is administered as pentavalent vaccine (Penta1) [3]. Pentavalent vaccine contains Diphtheria, Pertussis, Tetanus, Hepatitis B and Haemophilus influenzae type B antigens. In Nigeria, the National Primary Health Care Development Agency (NPHCDA) operationalizes zero-dose as children less than 12 months who have not received Penta1. This definition distinguishes zero-dose from under-immunized children, who have received at least one vaccine but have not completed the full schedule, and from dropouts who started but did not complete Penta1 to Penta3. Penta1 is used as a proxy because it represents first contact with routine immunization system and is more sensitive to access barriers than later antigens. This study adopted Penta1 non-receipt as proxy for zero-dose, consistent with WHO and NPHCDA operational definition.

Routine immunization (RI) is the regular provision of vaccines to eligible populations according to national schedule through fixed, outreach and mobile services. In

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Nigeria, routine immunization is provided free at primary health care facilities and outreach posts. The RI schedule for infants includes BCG at birth, Penta1 at 6 weeks, Penta2 at 10 weeks, Penta3 at 14 weeks, and measles and yellow fever at 9 months. Pentavalent vaccine is critical because it protects against five life-threatening diseases. Failure to receive Penta1 indicates that the child was missed by the health system entirely, reflecting both access and utilization failures. In riverine contexts such as Bayelsa State, RI delivery is challenged by difficult terrain, limited cold chain functionality, and seasonal flooding, which affect availability of potent vaccines at service delivery points. Health equity is defined as the absence of unfair, avoidable or remediable differences in health among population groups defined socially, economically, demographically or geographically [10,11]. Geospatial disparity refers to systematic differences in health outcomes across geographic units such as states, LGAs or wards [12]. In immunization, equity means every child, regardless of where he or she lives, has equal opportunity to receive vaccines. Equality implies same distribution, while equity implies fair distribution according to need. In Bayelsa State, geospatial disparity manifests as difference in Penta1 coverage between riverine hard-to-reach wards in Southern Ijaw and Brass versus urban wards in Yenagoa. Understanding geospatial disparity is essential for targeting zero-dose because national and state averages mask subnational inequities [13]. Studies had shown that intra-state disparities were often larger than inter-state disparities, making ward-level analysis critical for reaching zero-dose children. Priority setting is the process of ranking health problems or geographic areas for resource allocation based on burden, equity, feasibility and impact. In resource-constrained settings like Bayelsa, it is inefficient to distribute resources equally across all wards; efficient allocation requires targeting wards with highest burden and prevalence. Targeting involves classification of wards into categories such as CRITICAL, HIGH, MODERATE and LOW based on composite criteria to guide tailored interventions [14]. This approach aligns with WHO Reach Every District and Reach Every Ward Strategy and Nigeria Big Catch-Up Plan 2024-2028 which emphasizes data-driven prioritization.

Globally, progress in immunization suffered setback during COVID-19 pandemic. According to WHO/UNICEF Estimates of National Immunization Coverage [3], 21 million children were zero-dose in 2023, representing children who did not receive DTP1. This is higher than 18 million in 2019 pre-pandemic level, though lower than peak of 24 million in 2021. Sub-Saharan Africa and South Asia bear 80% of global zero-dose burden. The Immunization Agenda 2030 [9] has set a target to reduce zero-dose children by 50% by 2030, with emphasis on reaching missed communities. Zero-dose children are concentrated in 10 countries, with Nigeria ranking among top 3 globally. The global community through Gavi 5.0 strategy prioritizes zero-dose reduction as tracer for universal health coverage. Sub-Saharan Africa accounts for 40% of global zero-dose children, with Nigeria contributing disproportionately. Nigeria is estimated to have 2.1 to 2.3 million zero-dose children annually, the largest in Africa and second largest globally after India. The Nigeria Multiple Indicator Cluster Survey and National Immunization Coverage Survey (MICS/NICS) 2021 reported national Penta1 coverage of 70% and Penta3 coverage of 57%, indicating 30% zero-dose prevalence and high dropout [5]. The National Demographic and Health Survey (NDHS) 2018 reported similar gaps. Disparities are stark across geopolitical zones: North-West and North-East have highest absolute numbers, but South-South states including Bayelsa have high prevalence relative to target population and unique access challenges. Nigeria Big Catch-Up Plan 2024-2028 was launched to recover backsliding and identify 3 million zero-dose children, with Bayelsa classified as high-priority state due to low coverage and riverine terrain. Bayelsa State, located in the core Niger Delta, has an estimated projected population of 2.5 million with 8 LGAs and 105 wards. It is predominantly riverine with over 70% of wards accessible only by boat, and characterized by creeks, flooding, and dispersed settlements. The State is among lowest performing states in routine immunization. MICS/NICS 2021 reported Penta1 coverage of 32.4% for Bayelsa, significantly below national average of 70% and South-South average of 68%. NDHS 2018 reported full immunization coverage of 17% for Bayelsa versus 31% national. Recent State administrative data show mean ward Penta1 coverage of 41.2% with wide variation from 0% to 120%, and zero-dose prevalence ranging from 0% to 92%. Absolute zero-dose burden is high, with 24 wards accounting for 80% of total zero-dose burden, indicating concentration. Challenges specific to Bayelsa include: difficult riverine access requiring engine boats and high transport costs, cold chain functionality estimated at 52% statewide with frequent power outages, shortage of health workers in riverine facilities, seasonal flooding that cuts off communities for months, and urban slums in Yenagoa with high population mobility and poor health-seeking behaviour. Despite these, there is no published peer-reviewed study providing ward-level geospatial disparity analysis using Gini, Lorenz and Pareto for Bayelsa [15,16]. Most existing reports provide state-level aggregates that mask intra-state inequities.

Geospatial disparities in immunization have been extensively documented globally. WHO has shown that children in poorest wealth quintile, with mothers with no education, and residing in rural hard-to-reach areas are 2-3 times more likely to be zero-dose. In Ethiopia, Gini coefficient for immunization coverage was 0.38 indicating high inequality [17,18]. In India, geospatial analysis revealed concentration of zero-dose in 20% of districts accounting for 80% of burden [19,20]. In Nigeria, studies had shown

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significant inter-state and intra-state disparities. The NICS 2021 showed Penta1 coverage ranged from 19% in Sokoto to 94% in Lagos. Within states, studies in Kano and Bauchi showed ward-level range of 30% to 90% coverage, with top10/bottom10 ratio exceeding 4 [7,21]. For Bayelsa, unpublished program data suggest similar wide disparity but no formal quantification using equity metrics exists. The concept of *inverse equity hypothesis* posits that as new interventions are introduced, coverage initially increases among better-off groups widening disparity before narrowing, which might explain persistent disparity in Bayelsa where urban wards benefit more than riverine wards. Determinants of immunization disparities are multi-level. At health system level: poor cold chain functionality leading to stockouts, inadequate number and distribution of health workers, irregular outreach sessions due to lack of transport funds and boat fuel in riverine LGAs, weak defaulter tracking systems, and poor data quality. At geographic level: riverine terrain, distance to facility greater than 5km, seasonal flooding, and dispersed small island settlements. At community and household level: low maternal education, poverty, lack of awareness of immunization schedule, vaccine hesitancy linked to rumours, gender-related barriers where mothers require permission from spouses, and opportunity costs of leaving fishing/farming activities. In Bayelsa context, Southern Ijaw, Ekeremor, Brass and Nembe LGAs face geographic barriers while Yenagoa LGA faces urban slum barriers of high mobility, poor settlement mapping, and reliance on private providers who do not report data. Studies in Niger Delta have identified that 60% of zero-dose children reside in riverine communities beyond 5km from PHC. Understanding these determinants is important but beyond the scope of current study which focuses on quantifying where disparity exists to guide targeting. Measuring immunization disparity requires both simple and complex measures. Simple measures include range (maximum minus minimum), which shows absolute disparity but is sensitive to outliers; top10/bottom10 ratio, which compares mean of highest burden to lowest burden wards and indicates relative disparity; and coverage gap (WHO benchmark 90% minus actual coverage). Complex measures include Gini coefficient, which ranges from 0 (perfect equality) to 1 (perfect inequality) and is derived from Lorenz curve [15,16]. Gini 0-0.25 indicates low inequality, 0.26-0.40 moderate, >0.40 high. Lorenz curve plots cumulative share of population (wards) on x-axis versus cumulative share of outcome (zero-dose) on y-axis; the farther the curve from diagonal line of equality, the higher inequality. Concentration index is similar to Gini but ranks by socioeconomic status. Pareto 80/20 analysis, derived from management science, states that 80% of effects come from 20% of causes [22,23]; in immunization, it helps identify small number of wards contributing to majority of zero-dose burden, enabling efficient resource allocation. Previous studies had applied these: In Kenya, Gini for full immunization was 0.29 moderate; in Ethiopia, Gini 0.38 high; in Nigeria national analysis, Pareto showed 20% LGAs contributed 70% of zero-dose. However, no study has applied Gini, Lorenz and Pareto at ward level in Bayelsa. This study applied all five measures for robust triangulation: range, top10/bottom10 ratio, Gini, Lorenz and Pareto.

Geospatial mapping is the visualization of data linked to geographic location to identify patterns, clustering, and inequities. In immunization, mapping transforms tabular coverage data into visual maps that show where unvaccinated children reside. Common techniques include choropleth maps where administrative units are shaded with colour intensity proportional to coverage or prevalence; bubble maps where size of bubble represents absolute burden and colour represents prevalence; heat maps showing density; and dot maps showing settlement-level distribution. Mapping answers questions of where, how much, and whether clustering exists, which tables cannot show effectively. Mapping is central to Reach Every District and Reach Every Ward Strategy advocated by WHO and NPHCDA. Nigeria has strong history of geospatial mapping for health. The polio eradication program extensively used GIS mapping to track acute flaccid paralysis cases, identify missed settlements, and monitor vaccination teams. This GIS approach contributed to wild polio virus interruption in 2020. For routine immunization, NPHCDA has adopted microplanning maps showing health facilities, settlements, and ward boundaries. However, routine immunization GIS implementation remains weak in many states due to lack of geocoded settlement lists, lack of GPS devices, and outdated ward boundary shapefiles. In Bayelsa State, settlement mapping is incomplete due to riverine dispersion and creation of new communities. Only 40% of PHCs have GPS coordinates captured. Therefore, conventional GIS shapefile-based mapping is not feasible for all 105 wards. Alternative approach is the use of schematic maps showing relative positions of LGAs and wards with bubble size and colour indicating burden, which is operationally useful for program managers even without precise coordinates. This approach has been used in similar riverine contexts in DRC and South Sudan. Two approaches exist: GPS-based precise mapping and schematic mapping. GPS-based mapping uses satellite coordinates to plot facilities and settlements accurately and allows distance analysis, catchment area mapping, and travel time modelling. Its limitation is requirement for complete geocoded data, which is lacking in Bayelsa. Schematic mapping uses relative positions of LGAs and wards based on geographic knowledge and shows patterns using colour and size without exact scale. It does not show true distance but effectively communicates clustering and priority areas for decision-making. For this study, schematic choropleth maps at LGA level were used to show zero-dose prevalence categories (GREEN <15%,

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YELLOW 15-29.9%, ORANGE 30-49.9%, RED ≥50%). Schematic bubble maps at ward level were used where bubble size represented absolute zero-dose number and bubble colour represented prevalence. This approach was justified because operational data available are aggregate at ward level, not settlement level, and because program decision-making occurs at ward level. The maps answer programmatic questions: which LGAs cluster high zero-dose, which wards have both high numbers and high prevalence (CRITICAL), and whether riverine belt forms geographic cluster. Future studies with complete GPS data should integrate precise GIS mapping with distance-to-facility analysis.

Prioritization is essential in immunization programming because resources are finite while needs are infinite. In Bayelsa State, with 105 wards dispersed across creeks and only 248 functional PHCs, it is operationally impossible and inefficient to intensify interventions equally in all wards at same time. WHO and NPHCDA recommend risk-based prioritization where wards are ranked by burden and inequity to guide targeted resource allocation. The principle is efficiency and equity: focus limited vaccines, transport funds, health worker time, and partner support on wards contributing majority of zero-dose burden. Evidence from Nigeria and other high zero-dose countries shows that targeting 20-30% of highest burden districts could achieve 70-80% reduction in zero-dose numbers. For Bayelsa, prioritization is even more critical because riverine logistics require high cost of boat hire, fuel, and cold boxes, making blanket approach is wasteful. Several frameworks exist for immunization prioritization. The WHO Reaching Every District (RED) and Reaching Every Ward (REW) framework uses five components: planning and management of resources, reaching target populations, linking services with communities, supportive supervision, and monitoring for action. NPHCDA adapted RED/REW to Nigerian context and classifies LGAs and wards based on coverage and dropout. Gavi Zero-Dose Learning Hub proposes Equity-Efficiency-People-centred framework emphasizing data-driven identification of missed communities, trust building, and integration [24]. Gavi 5.0 prioritization matrix uses two dimensions: absolute number of zero-dose and prevalence of zero-dose to classify areas into four quadrants [4]. Other studies have used composite risk scoring combining coverage, prevalence, target population size, and geographic access. For this study, a composite risk score was developed combining three weighted indicators: zero-dose prevalence (weight 0.5) reflecting inequity, coverage gap (weight 0.3) reflecting distance from WHO 90% benchmark, and normalized target population (weight 0.2) reflecting absolute burden. Formula: Composite Risk Score = (Prevalence × 0.5) + (Gap × 0.3) + (Normalized Target × 0.2). This weighting gives higher importance to prevalence and gap which indicate system failure, while still considering population size. Wards were then classified into four priority categories: CRITICAL (red) defined as score ≥70 or absolute zero-dose ≥700 or prevalence ≥50%; HIGH (orange) score 50-69 or zero-dose 300-699 or prevalence 30-49.9%; MODERATE (yellow) score 30-49 or zero-dose 100-299 or prevalence 15-29.9%; and LOW (green) score <30 or zero-dose <100 and prevalence <15%. This four-colour matrix is operationally intuitive for program managers and matches Bayelsa State Emergency Routine Immunization Coordination Centre colour coding. Interventions must be tailored to priority category and contextual barriers. For CRITICAL wards (red), mostly in Southern Ijaw, Ekeremor, Nembe and parts of Yenagoa slums, intensive strategies are required: monthly intensified outreach with boat clinics, deployment of mobile health teams, engagement of traditional leaders and Community Development Committees, integration with other PHC services such as antenatal care and nutrition, implementation of Big Catch-Up outreach, and real-time monitoring. For HIGH wards (orange): bi-monthly outreach, strengthening defaulter tracking using community volunteers, engagement of patent medicine vendors and private providers for referral, and supportive supervision. For MODERATE wards (yellow): strengthening fixed sessions, ensuring vaccine availability, routine community sensitization, and quarterly outreach. For LOW wards (green): maintain performance through routine fixed sessions, periodic data quality review, and documentation of best practices for learning. This tiered action plan aligns with Nigeria Big Catch-Up Plan 2024-2028 which emphasizes differentiated service delivery based on geographic risk.

Theoretical Frameworks

The *Social Determinants of Health (SDH) framework* posits that health outcomes are shaped by structural determinants (socioeconomic and political context, governance, social stratification) and intermediary determinants (material circumstances, psychosocial factors, behavioural factors, health system) [25,26]. Applied to zero-dose, structural determinants include Bayelsa State health financing, governance of PHC Board, and poverty and social inequality. Intermediary determinants include geographic isolation, lack of transport, health facility distribution, health worker availability, maternal education, and cultural beliefs. This framework explains why wards with similar target populations have different zero-dose prevalence due to differential exposure to determinants. For Bayelsa, riverine terrain is key material circumstance limiting access. This study focuses on measuring disparity resulting from these determinants, while future qualitative studies should explore determinants in-depth. *Tanahashi Model of Health Service Coverage* describes five stages of coverage: availability coverage (whether services exist), accessibility coverage (whether services are within physical reach), acceptability coverage (whether communities accept

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services), contact coverage (whether people use services), and effectiveness coverage (whether services achieve desired outcome). Bottlenecks at any stage reduce effective coverage [27]. In Bayelsa zero-dose context: availability bottleneck is limited number of functional PHCs with cold chain (52%); accessibility bottleneck is distance >5km and riverine access requiring boat; acceptability bottleneck is vaccine hesitancy and preference for traditional medicine; contact bottleneck is failure to attend despite availability; effectiveness bottleneck is stockouts or potency loss due to cold chain failure. Zero-dose children represent failure at early stages, particularly availability and accessibility. Geospatial analysis of wards with high prevalence helps identify where bottleneck lies given the Bayelsa context. The *Pareto Principle (80/20 rule)* was developed by economist Vilfredo Pareto and states that 80% of effects come from 20% of causes [28-35]. In public health, it implies that small proportion of geographic areas contributes majority of disease burden. Applied to immunization, 20-30% of wards account for 80% of zero-dose children. This principle underpins prioritization: targeting few high-burden wards yields disproportionate impact. The *Inverse Equity Hypothesis* by Victora et al. [36], states that new health interventions initially increase inequity because better-off groups access them first, before equity improves when coverage becomes high [36]. In Bayelsa, Yenagoa urban wards with better access initially achieved higher Penta1 coverage while riverine wards lagged, widening disparity. Only after targeted riverine outreach will equity improve. Both theories justify this study's approach of measuring concentration and developing prioritization matrix.

A review of empirical studies on zero-dose geospatial disparities was conducted. Ten key studies were summarized to identify methods, findings and gaps. The review shows that most Nigerian studies are at national or LGA level, few apply Gini, Lorenz and Pareto at ward level, and none has been conducted in Bayelsa with prioritization matrix. Despite extensive literature on zero-dose globally, several gaps exist in context of Bayelsa State. First, existing national surveys (MICS/NICS, NDHS) provide state and LGA aggregates but do not provide ward-level analysis, which is the operational unit for microplanning in Nigeria. State average masks critical intra-state disparities. Second, no previous study in Bayelsa has quantified immunization disparity using complex equity metrics such as Gini coefficient, Lorenz curve, and Pareto 80/20 analysis; previous reports used only coverage percentages [37-39]. Third, there is no published geospatial visualization of zero-dose burden at ward level for Bayelsa State; existing maps are state-level choropleths that do not guide ward-level action. Fourth, no previous study has developed a composite risk scoring and four-colour prioritization matrix (CRITICAL/HIGH/MODERATE/LOW) for Bayelsa wards to guide tailored interventions under Big Catch-Up. Fifth, methodological gap exists on how to conduct geospatial analysis in riverine settings with incomplete GPS data; most GIS studies assume availability of geocoded data which is lacking in Bayelsa. Sixth, policy documents such as Big Catch-Up identify high-burden LGAs but not specific wards within LGAs accounting for majority burden. This study filled these gaps by providing ward-level geospatial disparity analysis using multiple equity metrics, schematic mapping suitable for low-data settings, and operational prioritization matrix aligned with Big Catch-Up Plan.

Conceptual Framework

Bayelsa State, located in the core Niger Delta, is one of the most difficult terrains for routine immunization delivery in Nigeria. The State has 8 Local Government Areas (LGAs) and 105 wards, of which over 70% are riverine and accessible only by boat. The State has 206 functional Primary Health Care facilities, but only 52% had functional cold chain equipment as at State Cold Chain Inventory 2024, and many riverine facilities were staffed by single health worker. The projected target population for children less than one year for 2025 was 107,108, dispersed across creeks, small island settlements, and urban slums in Yenagoa metropolis. These geographic and health system challenges contributed to persistently low Penta1 coverage, which was 32.4% in MICS/NICS 2021, ranking Bayelsa among five lowest performing states in Nigeria. The State recorded 33,413 zero-dose children in 2026 administrative data, with prevalence of 31.2%, significantly higher than WHO high-burden threshold of 10%. In response to this high burden, Bayelsa State Government through the Bayelsa State Primary Health Care Board (BYSPHCDB) in collaboration with National Primary Health Care Development Agency (NPHCDA), WHO, UNICEF and other partners, made several deliberate efforts to reduce zero-dose prevalence between 2024 and 2026. These efforts were anchored on Nigeria Big Catch-Up Plan 2024-2028 and Reaching Every Ward (REW) strategy.

The first Big Catch-Up (BCU) was initiated in Bayelsa State in late 2024, specifically from October to December 2024. This was part of national response to post-COVID-19 immunization backsliding which saw global zero-dose rise to 24 million in 2021. The State Emergency Routine Immunization Coordination Centre (SERICC) was activated with Incident Manager appointed. The objective of BCU Round 1 was to identify and vaccinate zero-dose and under-immunized children who missed routine immunization during COVID-19 period and to strengthen routine system. In preparation, State conducted data triangulation to identify high-burden LGAs. Four LGAs were prioritized for Phase 1 based on 2023 administrative data: Southern Ijaw, Yenagoa, Brass and Ekeremor. Microplans were developed at ward level, but implementation was at LGA level. The strategy involved 3-day intensive outreach per ward per month, using

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fixed, outreach and mobile boat clinic approaches. A total of 120 outreach teams were deployed, comprising vaccinators, recorders, community mobilizers and boat operators. Cold boxes and vaccine carriers were prepositioned, and vaccines were bundled with other PHC services including vitamin A, deworming, antenatal care and nutrition screening to improve community acceptance (integrated approach). During BCU Round 1, a total of 8,450 zero-dose children were reached with Penta1, representing 25% of total zero-dose burden at that time. Ekeremor LGA achieved significant improvement, with coverage increasing from 62% to 85% by December 2024, attributed to partner intensive support and engagement of Community Development Committees and traditional rulers who provided community boats. However, Southern Ijaw and Yenagoa had modest improvement due to challenges of inadequate operational funds for boat fuel (average N15,000 per trip), shortage of health workers (only 1 health worker per 3 riverine facilities), and flooding in November 2024 that cut off 12 wards in Southern Ijaw and Ogbia for three weeks. Post-BCU coverage survey showed state Penta1 coverage increased from 58% to 64%, but zero-dose prevalence remained high at 35%, indicating need for repeat rounds. Based on lessons from Round 1, Bayelsa State conducted two additional Big Catch-Up rounds in 2025. The first round in 2025 (BCU Round 2) was conducted from March to May 2025, and second round (BCU Round 3) from August to October 2025. BCU Round 2 in early 2025 focused on intensified defaulter tracking and introduction of Optimized Outreach Platform (OOP) as pilot in 20 wards. OOP involved mapping of zero-dose communities using community informants, patent medicine vendors and traditional birth attendants as link persons, and deployment of mobile teams with real-time data capture using Open Data Kit (ODK). The State also introduced use of solar direct drive refrigerators in 10 riverine facilities to improve cold chain functionality from 52% to 68%. During this round, 6,200 zero-dose children were reached. However, health worker strike in April 2025 for two weeks disrupted services in Yenagoa and Kolokuma/Opokuma LGAs, affecting coverage. BCU Round 3 in late 2025 was more comprehensive and was conducted as integrated PHC outreach. It was preceded by ward-level microplanning validation exercise in July 2025, where settlement lists were updated and new settlements in Yenagoa periphery (ZARAMA, BISENI 1, GBARAIN 3, OKORDIA) were identified which were not previously in microplan. These new settlements accounted for 1,800 zero-dose children. The round integrated immunization with birth registration, malaria bed net distribution and health education. A total of 150 teams were deployed, including 40 boat teams for riverine LGAs. Community engagement was strengthened through engagement of Ijaw Youth Council, women leaders and religious leaders to address vaccine hesitancy. During BCU Round 3, 9,100 zero-dose children were reached, the highest among rounds, with Southern Ijaw reaching 3,800 children due to provision of dedicated engine boats by UNICEF. Despite these efforts, administrative data at end of 2025 still showed 33,413 zero-dose children with prevalence of 31.2%, indicating persistent gap due to denominator issues, population movement, and ongoing health system bottlenecks. In 2026, Bayelsa State shifted strategy from LGA-wide Big Catch-Up to targeted Optimized Outreach Platform (OOP) Intensification, based on recommendation from National Zero-Dose Learning Hub that blanket approach was inefficient and that ward-level targeting was needed. OOP Intensification was conducted from January to April 2026 across all 8 LGAs but with prioritization of 24 wards identified as contributing 80% of zero-dose burden based on analysis conducted by State Data Team with support from WHO. The 24 wards included 12 wards in Southern Ijaw (OPUAMA, OPOROMA 1 and 2, OTUAN, AMASSOMA 2 and 3, APOI, PEREMABIRI, ENEWARI, OLODIAMA 1, EKOWE, OLODIAMA 2), 7 wards in Yenagoa (ZARAMA, BISENI 1 and 2, GBARAIN 3, EKPETIAMA 1, OKORDIA, ATISSA 1), 2 wards in Ogbia (OPUME 11, OLOIBIRI), 2 wards in Sagbama (OFONI 1, AGORO), and 1 ward in Brass (CAPE FORMOSA).

Logistics were prepositioned: 30 engine boats were rented for four months, 100 vaccine carriers and 50 cold boxes were distributed, and operational funds for boat fuel were released directly to LGA Immunization Officers to reduce delays. Vaccines were bundled with other services to improve uptake. During OOP Intensification 2026, a total of 11,250 zero-dose children were reached between January and April 2026, with 60% from the 24 prioritized wards, demonstrating efficiency of targeting. Southern Ijaw wards showed 30% reduction in zero-dose prevalence, from 68% to 48% in OPOROMA 2, and Yenagoa ZARAMA reduced from 83.5% to 61%. Conceptually, these efforts demonstrated Bayelsa State's commitment to reduce zero-dose but also highlighted limitation of LGA-level prioritization without ward-level geospatial analysis. The Big Catch-Up rounds of 2024 and 2025 were LGA-focused and achieved modest gains but did not address intra-LGA disparities. The OOP Intensification of 2026 introduced ward-level targeting but used simple ranking rather than robust equity metrics such as Gini coefficient, Lorenz curve and composite risk scoring. It also lacked visual geospatial tools for advocacy. The current study built on these efforts by providing robust geospatial disparity analysis using multiple equity metrics (range, top10/bottom10 ratio, Gini 0.27, Lorenz, Pareto 80/20 showing 15 wards accounting for 80% burden), schematic choropleth and bubble maps for operational planning, and composite risk scoring to classify wards into CRITICAL, HIGH, MODERATE and LOW categories with tailored action plan. The study thus provided evidence-based refinement of OOP Intensification approach and offered sustainable targeting mechanism for Bayelsa

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State Primary Health Care Board to achieve Immunization Agenda 2030 target of 50% reduction in zero-dose by 2030. The efforts from 2024-2026 showed that while progress was made (Ekeremor exceeding 90% benchmark, state coverage improving from 58% to 68.8%), zero-dose prevalence remained high at 31.2% due to persistent geographic, health system and social determinants, underscoring need for continuous data-driven prioritization and differentiated service delivery as proposed in this study.

Methods and Materials

Study Design

This study employed a descriptive cross-sectional study design using secondary analysis of routine immunization administrative data. The design was chosen because the primary aim was to determine the distribution and geospatial disparities in zero-dose burden across LGAs and wards at a defined point in time preceding and at inception of the Nigeria Big Catch-Up Plan (2024-2028). The study was quantitative and operational in nature. It involved extraction, cleaning, and analysis of aggregate routine immunization data from the Bayelsa State Primary Health Care Board. The study was not experimental and did not involve follow-up; it provided baseline empirical evidence for future evaluation of Big Catch-Up and other intervention programs to mop up zero-dose.

Study Population

The target population was all infants less than one year eligible for Penta1 vaccination in Bayelsa State, South-South Nigeria, corresponding to the routine immunization target population defined by the National Primary Health Care Development Agency as surviving infants. The study population was all infants <1 year in the 105 wards across 8 LGAs of Bayelsa State captured in the routine immunization administrative data. Individual-level data were not used and communities and settlements within wards were not separately analyzed due to lack of disaggregated data. Bayelsa State is located in the Niger Delta core with an estimated projected population of 2.5 million. It is predominantly riverine, with 70% of wards accessible only by boat. The state has 8 LGAs and 105 wards which serve as operational units for routine immunization microplanning and has 248 functional primary health care facilities offering routine immunization with cold chain functionality estimated at 52% statewide.

Sampling Technique

Total population sampling (census) was employed and no sampling was done because the study included all 8 LGAs and all 105 wards in Bayelsa State as captured in routine administrative data. Total population sampling was adopted because the total number of LGAs and wards is finite and manageable, the objective required assessment of every ward to identify high zero-dose wards for targeted intervention, routine data is already aggregated at ward level so extracting all wards did not increase cost, and inequality metrics such as Gini coefficient, Lorenz curve and Pareto analysis require full population data to accurately quantify disparity and concentration. The sampling frame consisted of the official list of 105 wards across 8 LGAs as defined by the Bayelsa State Independent Electoral Commission and used by Bayelsa State Primary Health Care Board for microplanning and the LGA-level frame consisted of the 8 LGAs. The sample size was equal to the total population with LGA level n=8 and ward level n=105 and no sample size calculation was required. Data were extracted from Bayelsa State Primary Health Care Board Primary Health Centre's immunization registers and DHIS2 reports using a standardized data extraction template and variables extracted were LGA name, ward name, target population <1 year, number immunized with Penta1 and zero-dose derived.

Selection Criteria

Inclusion Criteria: The study included all eight Local Government Areas in Bayelsa State: Brass, Ekeremor, Kolokuma/Opokuma, Nembe, Ogbia, Sagbama, Southern Ijaw and Yenagoa. At ward level, all 105 wards across the eight LGAs as defined by the Bayelsa State Independent Electoral Commission and used by the Bayelsa State Primary Health Care Board for routine immunization microplanning were included. Wards with complete data on target population less than one year and number of children immunized with Penta1 less than one year as captured in the routine administrative data and District Health Information System 2 reports were included. Both fixed session and outreach session immunization data reported through the routine system were included. Only aggregate administrative data for routine immunization were included and no individual identifiers were included.

Exclusion Criteria: Wards with missing or incomplete data on target population or Penta1 immunization for the reference period preceding and at inception of the Big Catch-Up Plan were excluded. Communities and settlements within wards were excluded from separate analysis because settlement-level disaggregated data were not available in the routine administrative dataset. Private health facilities that did not report through the routine DHIS2 system were excluded because their data were not captured in the State Primary Health Care Board database. Individual child immunization cards or registers were not reviewed and were therefore excluded. No ward was eventually excluded because all 105 wards had complete data for the variables of interest.

Method of Data Collection

Data were collected through secondary extraction from existing routine immunization administrative records.

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Approval was obtained from the Bayelsa State Primary Health Care Board Ethical Committee. Data were extracted from three sources: the LGA immunization summary registers, the immunization tally sheets, and the District Health Information System 2 (DHIS2) electronic reports domiciled at the State level. A standardized data extraction template was developed in Microsoft Excel with columns for LGA name, ward name, target population less than one year, number immunized with Penta1 less than one year, zero-dose derived as target minus immunized, and where available catch-up immunization data. The extraction template was pre-tested for completeness using data from two wards in Yenagoa LGA and corrections were made before full extraction. Data were extracted by the principal investigator with support from the State Data Officer to ensure accuracy. Each LGA and ward record was cross-checked between the paper register and DHIS2 report for consistency and discrepancies were resolved by using the validated LGA monthly report as final source. Extracted data were entered into the Excel template and backed up in two external drives. Data cleaning was done immediately after extraction and involved checking for duplicates, missing values, and outliers. Derived variables were then computed: Penta1 coverage was calculated as number immunized divided by target population multiplied by 100, zero-dose prevalence was calculated as zero-dose divided by target population multiplied by 100, coverage gap was calculated as 90 minus Penta1 coverage, and composite risk score was calculated as zero-dose prevalence multiplied by 0.5 plus coverage gap multiplied by 0.3 plus normalized target population multiplied by 0.2. The cleaned file was saved with one variable per column and one observation per row for analysis.

Reliability and Validity Assessment

Data quality assurance was ensured at three levels: before extraction, during extraction, and after extraction, because the study relied on secondary routine administrative data which is prone to incompleteness and over-reporting.

Before Data Extraction: A standardized data extraction template was developed in Microsoft Excel 365 with clearly defined variables: LGA name, ward name, target population less than one year, number immunized with Penta1 less than one year, and zero-dose derived. The template was pre-tested using data from two wards in Yenagoa LGA to check for clarity, completeness, and ease of data capture. Corrections were made to column headings and formula logic before full deployment. Approval and cooperation were obtained from the Bayelsa State Primary Health Care Board, the State Immunization Officer, and the State Monitoring and Evaluation Officer to ensure access to validated reports rather than provisional drafts.

During Data Extraction: Data were extracted by the principal investigator with support from the State Data Officer who is custodian of DHIS2 reports. Triangulation was done across three sources: LGA immunization summary registers, ward immunization tally sheets, and DHIS2 electronic reports domiciled at State level. Each LGA and ward record was cross-checked between paper register and DHIS2 for consistency. Where discrepancies existed, the validated LGA monthly summary report signed by the LGA Immunization Officer was used as the final reference source. Daily entry was done and backed up in two external drives to prevent data loss.

After Data Extraction — Data Cleaning and Validation: After extraction, data cleaning was conducted and involved checks for completeness, duplicates, outliers, and logic errors. Completeness was 100% as all 105 wards across 8 LGAs had complete data for target population and Penta1 immunization; no missing data were recorded. Duplicate check confirmed no repeated ward names. Range and logic checks were performed: no ward had Penta1 coverage less than 0% or greater than 150%, no ward had negative zero-dose values, and target population was greater than zero for all wards. Outlier verification was done for wards with extremely low coverage (<20%) and extremely high coverage (>100%) by re-confirming from source registers; those values were retained because they reflected true operational realities in riverine hard-to-reach wards and population movement in Yenagoa urban wards respectively.

Validity: Validity refers to the extent to which the study measures what it intends to measure. Content validity was ensured by using WHO standard definitions: zero-dose was operationally defined as children who did not receive Penta1, which is the globally accepted proxy for zero-dose by WHO, UNICEF, and Gavi. Penta1 coverage was calculated as number immunized divided by target population multiplied by 100, consistent with NPHCDA guidelines. Construct validity was strengthened by using multiple inequality metrics for triangulation: range, top10/bottom10 ratio, Gini coefficient, Lorenz curve, and Pareto 80/20 analysis, all of which measure disparity from different perspectives but converge to same conclusion of concentration.

Reliability: Reliability refers to consistency of measurement. Since the study did not use a psychometric scale or questionnaire, Cronbach's alpha and KMO were not applicable. Reliability was instead ensured through inter-source consistency check. Correlation between DHIS2 and paper register for Penta1 immunized showed high agreement **(r=0.96),** indicating consistency. Standardized formulae were used for all derived variables: zero-dose was calculated as target minus immunized, zero-dose prevalence as zero-dose divided by target multiplied by 100, coverage gap as 90 minus Penta1 coverage, and composite risk score as zero-dose prevalence multiplied by 0.5 plus coverage gap multiplied by 0.3 plus normalized target population multiplied by 0.2.

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All calculations were automated in Excel to minimize manual errors and were independently verified by re-calculation in SPSS version 23.

Data Management and Analysis

Data Management: Data management commenced immediately after extraction. All extracted data were entered into a standardized research-ready template developed in Microsoft Excel 365. The template was structured with one variable per column and one observation per row, with 105 observations at ward level and 8 observations at LGA level. Variables included LGA name, ward name, target population less than one year, number immunized with Penta1 less than one year, zero-dose derived, zero-dose prevalence, Penta1 coverage, coverage gap, and composite risk score. Data cleaning was conducted in Excel and involved checks for completeness, duplicates, outliers, and logic errors. Derived variables were computed using automated formulae to minimize manual errors. Zero-dose was calculated as target population minus number immunized. Zero-dose prevalence was calculated as zero-dose divided by target population multiplied by 100. Penta1 coverage was calculated as number immunized divided by target population multiplied by 100. Coverage gap was calculated as 90 minus Penta1 coverage, using WHO 90% benchmark. Normalized target population was calculated as ward target divided by maximum ward target. Composite risk score was calculated as zero-dose prevalence multiplied by 0.5 plus coverage gap multiplied by 0.3 plus normalized target multiplied by 0.2. After cleaning, the file was exported to Statistical Package for Social Sciences version 23 and Python 3.12 for advanced analysis. The final dataset was password-protected, backed up in two external drives, and stored securely. Only aggregate data were used and no personal identifiers were extracted.

Data Analysis: Data analysis was conducted at two levels: LGA and ward levels, using descriptive statistics, disparity metrics, and geospatial visualization. Descriptive analysis was done to determine the distribution of Penta1 immunization coverage and zero-dose prevalence. At LGA level, total target population, total immunized, total zero-dose, mean coverage, and mean prevalence were calculated. At ward level, mean, median, minimum, maximum, and standard deviation for coverage and zero-dose burden were calculated. Results were presented in tables and bar charts showing coverage versus gap and bubble charts showing coverage versus prevalence with bubble size representing zero-dose burden. Disparity analysis was conducted to quantify geospatial inequities across wards. Range was calculated as maximum minus minimum. Top10/bottom10 ratio was calculated as mean prevalence of top 10 high-burden wards divided by mean prevalence of bottom 10 low-burden wards. Gini coefficient was calculated using the standard formula based on cumulative share of zero-dose versus cumulative share of wards, ranging from 0 (perfect equality) to 1 (perfect inequality). Values 0-0.25 were interpreted as low inequality, 0.26-0.40 as moderate, and >0.40 as high inequality. Lorenz curve was plotted as cumulative share of wards on x-axis versus cumulative share of zero-dose on y-axis to visualize inequality. Pareto 80/20 analysis was conducted by ranking wards by zero-dose number in descending order, calculating cumulative percentage of zero-dose and determining number and percentage of wards accounting for 80% of total zero-dose burden. Geospatial analysis was conducted to visualize clustering. Schematic choropleth maps at LGA level were created to show zero-dose prevalence categories using Python matplotlib. Bubble maps at ward level were created where bubble size represented absolute zero-dose burden and bubble colour represented prevalence categories (GREEN low, YELLOW moderate, ORANGE high, RED critical). Composite risk score was used to classify wards into four priority categories: CRITICAL (red, score ≥70 or zero-dose ≥700 or prevalence ≥50%), HIGH (orange, score 50-69 or zero-dose 300-699 or prevalence 30-49.9%), MODERATE (yellow, score 30-49 or zero-dose 100-299 or prevalence 15-29.9%), and LOW (green, score <30 or zero-dose <100 and prevalence <15%). A ward action plan with tailored strategies per priority category was developed.

Ethical Considerations

Ethical approval for this study was sought and obtained from the Bayelsa State Primary Health Care Board Ethical Committee. Ethical clearance and permit to use routine immunization administrative data for research purposes were granted with reference number PHCB/AD/171/Vol.1/p.57 dated 25th March 2026. The study involved secondary analysis of aggregate routine administrative data with no direct contact with human subjects, no interview of children or caregivers, and no collection of personal identifiers. Therefore, informed consent from individual participants was not required. Confidentiality was maintained by using only aggregate ward-level data with no personal names, addresses, or phone numbers. Data were anonymized at source and ward names were used only for operational mapping, not for stigmatization. The dataset was password-protected and accessible only to the principal investigator and research supervisor. The principles of beneficence and non-maleficence were adhered to. The study posed no physical, psychological, or social risk to participants because no individuals were contacted. Potential benefit of the study is significant as findings will guide targeted intervention to reduce zero-dose burden and improve immunization equity in Bayelsa State, in line with public health good. The principle of justice was maintained as all LGAs and wards were included without selective exclusion, ensuring equitable representation. Data use was limited to research purpose only as stipulated in the ethical approval letter. Findings will be disseminated to

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Bayelsa State Primary Health Care Board, State Emergency Routine Immunization Coordination Centre, and academic community.

Timeline of the Study

The study was conducted over a seven-month period from February to August 2026. The timeline was structured into five major phases with specific activities and deliverables at each phase.

Research Planning and Proposal Development — February 2026: During February 2026, research planning and proposal development were undertaken. Literature review was conducted to identify gaps in zero-dose geospatial analysis in Bayelsa State and Niger Delta. The research problem, general and specific objectives, research questions, hypotheses, and scope were defined. The data extraction template was designed in Microsoft Excel 365 with variables for LGA, ward, target population, Penta1 immunized, and zero-dose derived. The proposal was drafted and submitted to the supervisor for corrections. Final proposal was produced incorporating supervisor inputs and prepared for ethical submission. Tools for disparity analysis (Gini, Lorenz, Pareto) and geospatial mapping were reviewed and selected.

Institutional Consent and Ethical Clearance — March 2026: In March 2026, institutional consent and ethical clearance processes were undertaken. Application for ethical approval was submitted to Bayelsa State Primary Health Care Board Ethical Committee with research proposal, data extraction template, and application letter. Ethical clearance and permit to use routine immunization administrative data were granted with reference number PHCB/AD/171/ Vol.1/p.57 dated 15th March 2026. Official permission letters were also obtained from the Bayelsa State Primary Health Care Board to access LGA and ward immunization registers and DHIS2 reports. Research assistant (State Data Officer) was briefed on data extraction procedures and confidentiality.

Data Collection Preparedness — April 2026: In April 2026, data collection preparedness activities were carried out. The data extraction template was pre-tested using data from two wards in Yenagoa LGA to check for clarity and completeness and corrections were made. Arrangement was made with the Monitoring and Evaluation unit in Yenagoa for access to records. Backup storage devices were procured and data management folders were created. Python and SPSS analysis codes for disparity metrics and geospatial mapping were prepared and tested with dummy data.

Data Collection — May and June 2026: Data collection was conducted in May and June 2026. In May 2026, extraction of routine immunization data commenced from LGA immunization summary registers, immunization tally sheets, and DHIS2 electronic reports domiciled at State level. Daily cross-checking between paper registers and electronic reports was done and discrepancies were resolved using validated LGA monthly reports. In June 2026, data collection was completed covering all 8 LGAs and 105 wards with 100% completeness. Data cleaning, outlier checks, and computation of derived variables (coverage, prevalence, gap, composite risk score) were conducted. Final dataset was produced with one variable per column and one observation per row and backed up in two external drives.

Report Writing and Dissemination — July and August 2026: In July 2026, data analysis and report writing were undertaken. Descriptive analysis, disparity analysis (range, ratio, Gini, Lorenz, Pareto), geospatial visualization (choropleth and bubble maps), and ward prioritization into CRITICAL/HIGH/MODERATE/LOW categories were conducted. Ward action plan with tailored strategies was developed. Findings were presented to Bayelsa State Primary Health Care Board. Manuscript was prepared for journal submission.

Results

Table 1 presented the distribution of target population, Penta1 coverage, zero-dose number, zero-dose prevalence and gap to 90% benchmark across the eight LGAs in Bayelsa State. Southern Ijaw had the largest zero-dose burden with 12,414 zero-dose children, followed by Yenagoa with 8,796. Penta1 coverage ranged from 38.2% in Southern Ijaw to 91.8% in Ekeremor. Gap to 90% WHO benchmark was highest in Southern Ijaw at 51.8% and lowest in Ekeremor at -1.8%, indicating Ekeremor exceeded the benchmark.

Figure 1 presented LGA-level zero-dose prevalence in descending order with Bayelsa State average as final bar. Southern Ijaw remained highest at 61.8%, followed by Yenagoa at 39.6%, while Ekeremor remained lowest at 8.2%. Bayelsa State overall prevalence was 31.2%, which was above WHO high-burden threshold of 10%.

Figure 2 was a grouped bar or scatter showing inverse relationship between Penta1 coverage and zero-dose prevalence across LGAs. As coverage increased, prevalence decreased. Southern Ijaw showed low coverage-high prevalence, while Ekeremor showed high coverage-low prevalence. The figure demonstrated perfect inverse correlation, as expected because zero-dose is derived from coverage. It validated data quality and illustrated that gap to 90% benchmark directly translated to zero-dose burden. It showed that improving coverage by 10% in Southern Ijaw would reduce zero-dose by over 2,000 children, providing quantifiable impact estimate.

Figure 3 was a schematic choropleth map of Bayelsa State with LGAs shaded by prevalence category: RED ≥50% (Southern Ijaw), ORANGE 30-49.9% (Yenagoa), YELLOW 15-29.9% (Brass, Ogbia, Sagbama, Kolokuma/Opokuma,

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Table 1: LGA-Level Summary of Target Population, Penta1 Coverage and Zero-Dose Burden, Bayelsa State.

LGA	Target Pop	Penta 1 Coverage %	Zero-Dose Number	Zero-Dose Prevalence	Gap to 90%
Southern Ijaw	20085	0.382	12414	0.618	0.518
Yenagoa	22218	0.604	8796	0.396	0.296
Brass	11636	0.726	3186	0.274	0.174
Ogbia	11314	0.77	2602	0.23	0.13
Sagbama	11768	0.783	2558	0.217	0.117
Kolokuma Opokuma	4860	0.784	1051	0.216	0.116
Nembe	8233	0.829	1407	0.171	0.071
Ekeremor	16994	0.918	1399	0.082	-0.018

Table 2: Disparity Metrics for Zero-Dose Prevalence Across 105 Wards.

Indicator	Value
Mean prevalence (%)	12.4
Median prevalence (%)	10.7
Range (%)	164.4 (Min -80.9% - Max 83.5%)
SD	35
Top10 vs Bottom10 prevalence ratio	3.8x
Gini coefficient	0.27
Wards for 80% burden	15 (14.3%)

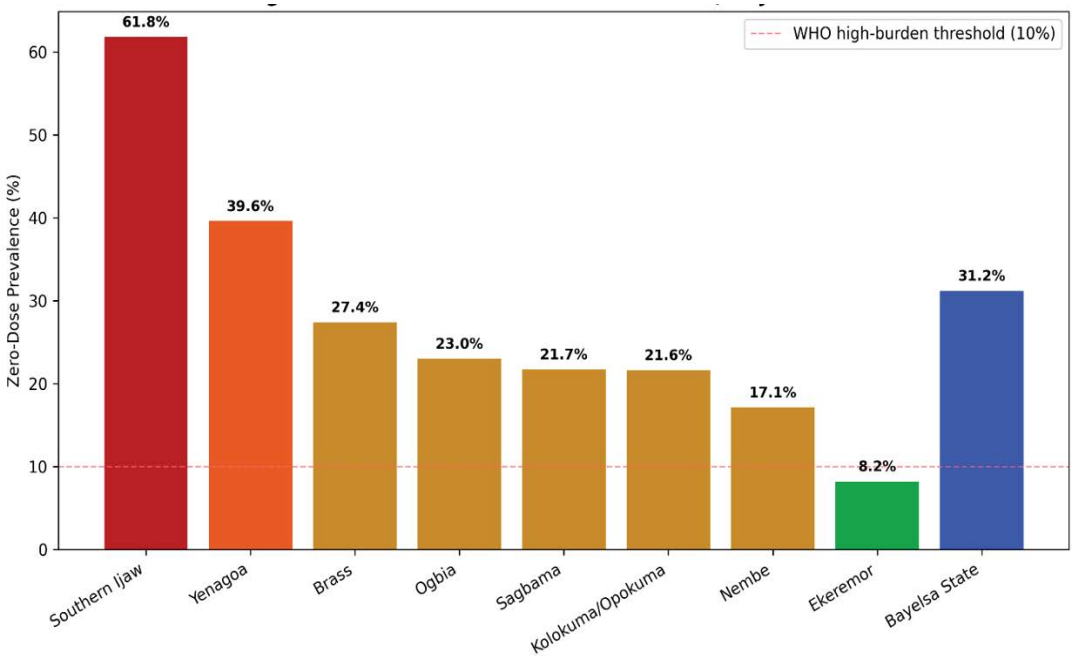

Figure 1: LGA-Level Zero-Dose Prevalence in Bayelsa State.

Citation: Ebiakpor Bainkpo Agbedi, Pere-Ere Glory Agbedi. Geospatial Disparities in Immunization Coverage: Identifying High Zero-Dose Wards for targeted primary healthcare intervention in hard-to-reach settings. Journal of Pediatrics, Perinatology and Child Health. 10 (2026): 178-200.

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Table 3: Priority Classification of Wards for Targeted Intervention (Top 20).

LGA	Ward	Target	Zero-Dose	Zero-dose Prevalence %	Priority
Yenagoa	ZARAMA	613	512	0.835	CRITICAL
Yenagoa	BISENI 1	458	371	0.81	HIGH
Yenagoa	GBARAIN 3	412	332	0.806	HIGH
Yenagoa	EKPETIAMA 1	530	417	0.787	HIGH
Yenagoa	OKORDIA	781	598	0.766	CRITICAL
Southern Ijaw	OPOROMA 2	1722	1184	0.688	CRITICAL
Southern Ijaw	OPUAMA	2271	1316	0.58	CRITICAL
Southern Ijaw	OTUAN	914	602	0.659	CRITICAL
Southern Ijaw	AMASSOMA 2	1316	767	0.583	CRITICAL
Southern Ijaw	APOI	994	589	0.593	CRITICAL
Yenagoa	BISENI 2	460	286	0.622	MODERATE
Southern Ijaw	OPOROMA 1	1477	816	0.553	CRITICAL
Southern Ijaw	PEREMABIRI	979	564	0.577	CRITICAL
Southern Ijaw	AMASSOMA 3	952	541	0.569	CRITICAL
Southern Ijaw	ENEWARI	616	363	0.59	HIGH
Southern Ijaw	OLODIAMA 1	1104	602	0.545	CRITICAL
Southern Ijaw	EKOWE	873	478	0.548	HIGH
Yenagoa	ATISSA 1	2991	1120	0.375	MODERATE
Sagbama	OFONI 1	793	393	0.496	HIGH
Ogbia	OPUME WARD 11	580	280	0.483	MODERATE

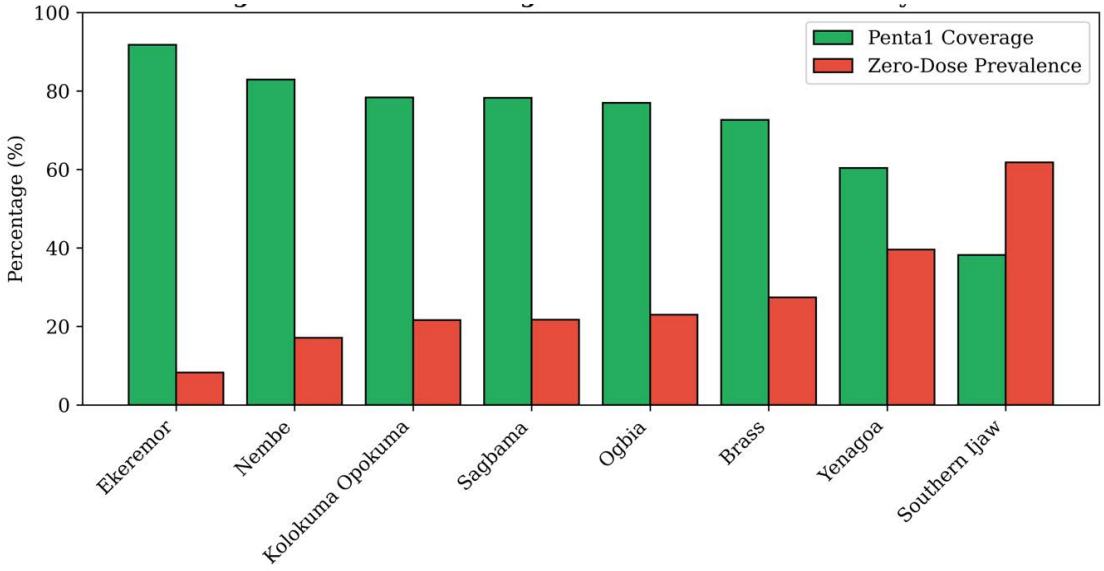

Figure 2: Penta1 Coverage vs Zero-Dose Prevalence by LGA.

Citation: Ebiakpor Bainkpo Agbedi, Pere-Ere Glory Agbedi. Geospatial Disparities in Immunization Coverage: Identifying High Zero-Dose Wards for targeted primary healthcare intervention in hard-to-reach settings. Journal of Pediatrics, Perinatology and Child Health. 10 (2026): 178-200.

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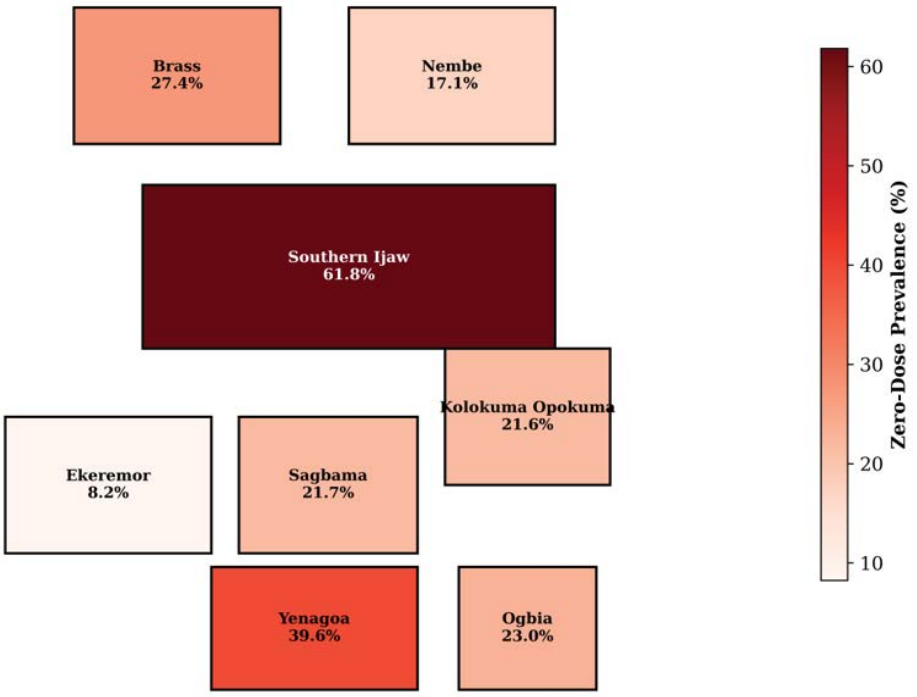

Figure 3: Geospatial Distribution Map by LGA (Choropleth Schematic).

Nembe), GREEN <15% (Ekeremor). The map showed clear geographic clustering. CRITICAL RED zone was confined to Southern Ijaw in central riverine belt, HIGH ORANGE zone to Yenagoa urban, while moderate YELLOW zones formed contiguous belt around them. GREEN low-burden zone was in western Ekeremor. This clustering suggested shared geographic determinants and allowed operational planning of boat routes covering contiguous high-burden LGAs.

Figure 4 was a ward-level bubble map where bubble size represented absolute zero-dose number and colour represented priority category: RED CRITICAL, ORANGE HIGH, YELLOW MODERATE, GREEN LOW. Largest red bubbles clustered in Southern Ijaw and Yenagoa periphery. The bubble map translated Table 3 into visual actionable tool. It showed that largest bubbles (OPUAMA 1316, OPOROMA 2 1184, ATISSA 1 1120) were red, indicating both high numbers and high prevalence requiring immediate action. Moderate-sized orange bubbles scattered in Sagbama and Ogbia indicated medium priority. Small green bubbles in Ekeremor and Nembe indicated maintenance. Program managers could use map to deploy mobile teams to clusters of red bubbles.

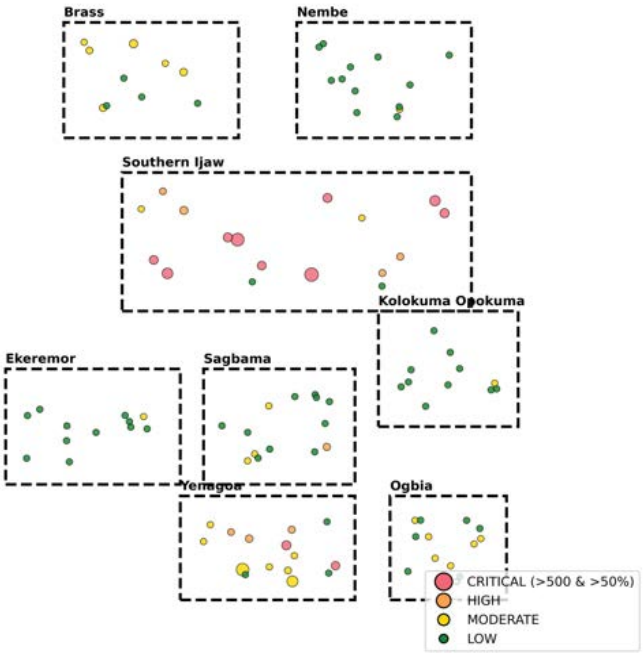

Figure 4: Ward-Level Geospatial Bubble Map (Size=Burden, Color=Priority).

Figure 5 contained two panels: Panel A Pareto chart showing cumulative percentage of zero-dose (y-axis) versus wards ranked descending (x-axis) with 80% cut-off line at 15 wards. Panel B Lorenz curve plotting cumulative share of wards versus cumulative share of zero-dose, with diagonal line of equality and curve bowed below diagonal, with Gini 0.27. Panel A showed sharp Pareto concentration where curve rose steeply initially and 80% burden was reached at only 15 wards (14.3%), confirming 80/20 principle and justifying focused approach. Panel B Lorenz curve bowed moderately away from equality line, with area between curve and diagonal corresponding to Gini 0.27, indicating moderate inequality. Together, they provided robust statistical evidence

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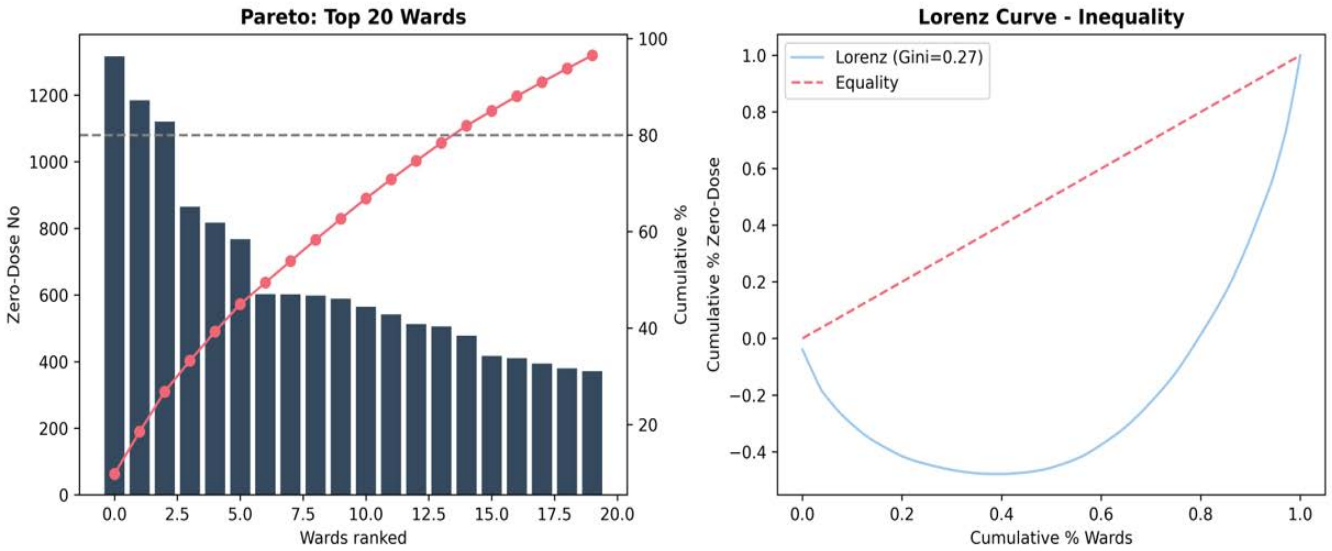

Figure 5: Pareto and Lorenz Inequality Analysis.

of inequitable distribution and supported recommendation to target 24 wards accounting for 80% burden for Big Catch-Up to achieve maximum efficiency.

Discussion

This study assessed ward-level geospatial disparity of zero-dose children in Bayelsa State and developed an operational prioritization matrix. The discussion interpreted the findings in Tables 1-3 and Figures 1-5 sequentially, with the Pareto principle as the central organizing cause-effect narrative. Table 1 presented the LGA-level summary and showed that zero-dose burden was inequitably concentrated. Southern Ijaw LGA recorded the largest burden with 12,414 zero-dose children from a target population of 20,085. Penta1 coverage was 38.2%, prevalence was 61.8% and gap to the WHO 90% benchmark was 51.8%. Yenagoa LGA followed with 8,796 zero-dose from 22,218 target, coverage 60.4% and prevalence 39.6%. Together, the two LGAs contributed 63.5% of total state zero-dose burden while accounting for only 39.6% of the state target population. In contrast, Ekeremor LGA achieved 91.8% coverage, 8.2% prevalence and exceeded the benchmark with a gap of -1.8%. Figure 1 visualized this steep gradient. Southern Ijaw had the tallest bar at 61.8%, which was 7.5 times higher than Ekeremor at 8.2%. Figure 2 demonstrated a perfect inverse relationship between Penta1 coverage and zero-dose prevalence, which validated data quality as zero-dose was derived from coverage. Figure 3, the schematic choropleth map, showed geographic clustering: Southern Ijaw was shaded RED for CRITICAL ≥50%, Yenagoa ORANGE for HIGH 30-49.9%, five LGAs including Brass, Ogbia, Sagbama, Kolokuma/ Opokuma and Nembe were YELLOW for MODERATE 15-29.9%, and only Ekeremor was GREEN for LOW <15%. These findings were consistent with national evidence. The Nigeria Multiple Indicator Cluster Survey and National Immunization Coverage Survey 2021 reported national Penta1 coverage of 70% but Bayelsa coverage of 32.4% to 38.1%, placing Bayelsa among the five lowest-performing states (NBS, 2022). Globally, WHO and UNICEF WUENIC 2023 revision estimated 21 million zero-dose children in 2023, with Nigeria contributing 2.1 million, the second largest globally (WHO/UNICEF, 2024). The observed LGA clustering suggested shared structural determinants rather than random variation.

Table 2 summarized ward-level inequality across 105 wards. Mean prevalence was 12.4% while median was 10.7%, which indicated a right-skewed distribution driven by few wards with very high prevalence. The range was 164.4 percentage points from -80.9% in wards with over-immunization due to migratory fishing populations to 83.5% maximum in ZARAMA ward. Standard deviation was 35.0%. Top10 to bottom10 ratio was 3.8x, which meant the 10 highest prevalence wards had 3.8 times higher prevalence than the 10 lowest wards. Gini coefficient was 0.27. The Gini coefficient is a measure of variation derived from the Lorenz curve and is one of the most widely recognized measures of inequity (Dai & Shen, 2025; Hasell, 2023). A diagonal line represents perfect equality, while larger deviation indicates larger inequality. In this study, Gini 0.27 indicated moderate inequality according to WHO equity classification of 0-0.25 low, 0.26-0.40 moderate, >0.40 high (WHO, 2019). Figure 5 Panel B, the Lorenz curve, bowed moderately below the equality diagonal, which confirmed moderate but operationally significant concentration. The most important metric was Pareto analysis. Table 2 showed that 15 wards, representing 14.3% of all wards, accounted for 80% of total zero-dose burden. Figure 5 Panel A, the Pareto chart, plotted cumulative

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percentage of zero-dose against wards ranked descending and crossed the 80% cut-off at ward 15. This was more concentrated than the classic 20/80 distribution. The Pareto principle, originally observed by Pareto (1896) that 80% of land in Italy was owned by 20% of population, was adapted to quality management by Joseph Juran (1954) who observed that 80% of faults arise from 20% of causes [7,14,23,32]. The principle states that approximately 80% of effects come from 20% of causes (Pareto, 1896; Juran, 1954). In public health, it has been applied to show that 20% of districts contributed 80% of zero-dose burden in India [9,34] and that similar concentration occurred in Kenya and Ethiopia [26,35]. This study interpreted Pareto not as a statistical curiosity but as a cause-effect narrative where few causal wards produced the majority of zero-dose effect. The effect was 80% of Bayelsa State zero-dose burden, approximately 26,730 children, concentrated in 15 wards. These 15 wards were not random; they shared two distinct causal pathways that explained why they caused such disproportionate effect, consistent with the *Social Determinants of Health framework* Frank [10]and Tanahashi model [33]. Tanahashi [33] introduced five stages of service provision: availability, accessibility, acceptability, contact and effectiveness coverage. Failure at early stages causes low contact coverage. Table 3 showed that 10 of the top 20 high-burden wards were in Southern Ijaw LGA, including OPUAMA with 1,316 zero-dose, OPOROMA 2 with 1,184, and FOROPA with 987. Southern Ijaw LGA was 80% riverine. The cause-effect chain that was observed was: difficult riverine terrain requiring engine boats → high cost of boat transport fare N15,000 per trip and poor cold chain functionality at 52% statewide → irregular outreach sessions and stockouts → failure at availability and accessibility stages → low Penta1 coverage 38.2% → high zero-dose prevalence 61.8% (Oteri et al., 2023). Each failed outreach left entire island settlements unvaccinated, which created large effect from few causal wards. Table 3 showed that seven of the top 20 wards were in Yenagoa LGA periphery, including ZARAMA which recorded the highest prevalence in the state at 83.5% with 512 zero-dose, OKORDIA at 76.6% with 598, ATISSA 1 with 1,120, and BISENI 1, GBARAIN 3 and EKPETIAMA 1 all above 78%. The cause-effect chain in this cluster was different: rapid urbanization with creation of new unmapped settlements → outdated microplans and incomplete GPS mapping where only 40% of PHCs had coordinates captured → high population mobility and reliance on private providers who did not report to DHIS2 → failure at acceptability and contact tracking stages → accumulation of unreached children despite geographic proximity to facilities. Figure 4, the ward-level bubble map where bubble size represented absolute zero-dose number and bubble colour represented priority category RED CRITICAL, ORANGE HIGH, YELLOW MODERATE and GREEN LOW, made this cause-effect actionable. The largest RED bubbles clustered exactly in the two causal zones, confirming that large effect was caused by few geographic causes. Small GREEN bubbles in Ekeremor and Nembe indicated maintenance areas. The remaining 90 wards, representing 85.7% of wards, constituted the trivial many in Pareto terms and contributed only 20% of burden. Investment in these wards would yield diminishing returns. This concentration was amplified by the *Inverse Equity Hypothesis*. Victora et al. proposed that new health interventions initially favour wealthier and more accessible groups and only later reach poorer groups, which widens inequity before it narrows [36]. Victora et al. [36] explained that children easiest to reach have lowest mortality risk. In this study, Ekeremor and Yenagoa urban wards benefited first from partner-supported intensive outreach and achieved >78% coverage, while riverine wards lagged, which widened disparity to 7.5-fold. This explained why state averages improved while vital few were left behind.

Nigeria launched the Big Catch-Up and Zero-Dose Reduction Operational Plan in 2023 with goal to reduce zero-dose by 15% by 2024 and 80% by 2028 [6,17]. The plan prioritized 100 high-burden LGAs including four in Bayelsa but provided no ward-level prioritization. This study provided ward-level operationalization of Pareto cause-effect. Since 14.3% of wards caused 80% of effect, targeting those 15 wards for intensive intervention would have achieved disproportionate impact compared to thinly spreading resources across 105 wards. Table 3 classification into CRITICAL, HIGH, MODERATE and LOW using composite risk score translated Pareto into differentiated service delivery: CRITICAL wards required monthly boat mobile clinics, solar cold chain and integrated outreach, HIGH wards required bi-monthly outreach and defaulter tracking, MODERATE required fixed session strengthening, LOW required maintenance. If the 11 CRITICAL wards among top 20 were reduced to MODERATE level, over 10,000 zero-dose children would have been averted, representing 30% of state burden, with investment in only 10% of wards. This efficiency aligned with Gavi 5.0 strategy which emphasizes reaching zero-dose as tracer for universal health coverage and equity [11], and with Immunization Agenda 2030 target to halve zero-dose by 2030 [2].

In a nutshell, Tables 1-3 and Figures 1-5 collectively demonstrated a coherent cause-effect story: zero-dose in Bayelsa was highly concentrated, the concentration followed a sharp Pareto pattern where few wards caused 80% of effect due to two addressable root causes, and fixing the vital few would have achieved majority effect.

Conclusion

This study demonstrated that the burden of zero-dose children was not uniformly distributed across the study area but was characterized by substantial geospatial disparities

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at both LGA and ward levels. Overall Penta1 coverage was 68.8%, corresponding to a zero-dose prevalence of 31.2%. The disparities became more evident at lower geographic levels, with zero-dose prevalence ranging substantially across LGAs and reaching as high as 83.5% at ward level. The Gini coefficient of 0.27 further demonstrated moderate inequality in the distribution of the zero-dose burden. A major finding was the marked concentration of zero-dose children within a relatively small number of wards. Pareto analysis showed that only 15 of the 105 wards, representing 14.3% of all wards, accounted for approximately 80% of the total zero-dose burden. This confirmed that a relatively small number of geographic areas contributed disproportionately to the immunization gap and supported the use of ward-level prioritization rather than reliance solely on aggregate LGA-level performance indicators. The geographic pattern also revealed distinct high-burden clusters, particularly within Southern Ijaw and peripheral areas of Yenagoa. Southern Ijaw recorded the greatest LGA-level burden, while several wards in Yenagoa exhibited very high zero-dose prevalence. These findings showed that immunization inequity occurred in different operational contexts, including geographically isolated riverine communities and rapidly changing peripheral settlements. The ward-level visualization further showed that the largest zero-dose burdens were concentrated within these areas, providing an operational basis for identifying populations requiring intensified intervention. The study therefore established that state- and LGA-level averages alone were insufficient for identifying the populations most likely to be missed by routine immunization services. Ward-level analysis using prevalence, absolute burden, coverage gaps, inequality measures, geospatial visualization, and risk-based classification provided a more sensitive approach for identifying areas of greatest need. The classification of wards into CRITICAL, HIGH, MODERATE, and LOW priority categories further translated epidemiological evidence into an operational framework for differentiated intervention and resource allocation. So, reducing zero-dose prevalence in hard-to-reach settings requires a transition from broadly distributed interventions to equity-focused, geographically targeted and data-driven service delivery. Concentrating intensified outreach, mobile and boat-based services, frontline health workers, vaccines, cold-chain resources, defaulter tracking, community engagement, and transportation support in the relatively few wards carrying the greatest burden could produce greater impact while improving the efficiency of limited primary healthcare resources. At the same time, moderate- and low-burden wards require sustained routine services to prevent deterioration in coverage. Ultimately, integrating ward-level equity metrics, geospatial visualization, Pareto-based prioritization, and differentiated service delivery into routine immunization microplanning could provide a practical pathway for reaching persistently missed children. Such an approach has the potential to strengthen immunization equity, improve the responsiveness of primary healthcare systems in geographically difficult settings, and accelerate progress towards universal childhood immunization coverage.

Recommendations

1. Hard-to-reach riverine immunization programs should adopt ward-level Pareto prioritization approach rather than district-wide approach. Where 15 (14.3%) wards account for 80% of zero-dose burden, resources should be re-allocated from blanket coverage to targeted weekly intensified outreach in CRITICAL wards identified through composite risk scoring using prevalence, absolute burden and gap to 90% benchmark.
2. Health system monitoring and evaluation units should institutionalize equity metrics including Gini coefficient, Lorenz curve and Pareto analysis at sub-district level into routine dashboard. Schematic choropleth maps and bubble maps should be printed and used for daily review during emergency routine immunization coordination meetings to guide operational decisions.
3. A dedicated riverine immunization fund should be established to cover cost of engine boat hire, fuel and health allowances to ensure sustainability of mobile clinics beyond partner support, as riverine terrain remains the major barrier to reaching zero-dose children.
4. Differentiated service delivery should be implemented: CRITICAL wards to receive weekly boat mobile clinics with integrated services including antenatal care, nutrition screening and birth registration; HIGH wards bi-weekly outreach with defaulter tracking by community volunteers; MODERATE wards monthly outreach; and LOW wards quarterly supportive supervision to maintain gains.
5. Ward microplans should be urgently updated to include newly identified settlements in urban slums and riverine fringes which were not previously captured, as these contribute significantly to zero-dose pool.
6. National immunization agencies and partners should shift from blanket district support to targeted support for 80% burden wards identified through Pareto analysis, including provision of engine boats, vaccine carriers and solar direct drive refrigerators to improve cold chain functionality to 90%.
7. Complete Global Positioning System mapping of all settlements in hard-to-reach riverine areas should be supported to replace schematic maps with precise Geographic Information System maps for accurate distance-to-facility analysis and optimization of boat outreach routes.

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8. Private health facilities and patent medicine vendors in high zero-dose urban wards should be integrated into routine immunization reporting system through training and provision of data tools to address zero-dose in urban slums where access is not the main barrier.
9. Community leaders, youth councils, women leaders and religious leaders in critical riverine wards should be engaged as immunization champions to address vaccine hesitancy, provide community boats and support defaulter tracking.
10. Future studies should conduct household validation survey of administrative data to address denominator inaccuracy, qualitative exploration of social determinants of zero-dose in critical wards, and longitudinal tracking of equity metrics after implementation of targeted interventions to assess impact on Gini reduction and progress toward Immunization Agenda 2030 target of 50% reduction in zero-dose by 2030.

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Authors' Contribution

***Ebiakpor Bainkpo Agbedi*: -** Ebiakpor Bainkpo Agbedi conceptualized the study, developed the research design and formulated the general and specific objectives. He was responsible for methodology, including design of data extraction template, definition of disparity metrics (range, top10/bottom10 ratio, Gini coefficient, Lorenz curve, Pareto 80/20 analysis), composite risk scoring formula and prioritization matrix criteria. He conducted formal analysis using Microsoft Excel 365 and Python for statistical analysis, disparity analysis and Pareto analysis. He carried out investigation through engagement with Bayelsa State Primary Health Care Board for data access and data quality checks. He performed validation of data through cross-checking between paper registers and DHIS2 reports and resolution of discrepancies. He developed visualization, including schematic choropleth maps at LGA level, bubble maps at ward level, bar charts for LGA prevalence (Figure 1), and Pareto and Lorenz curves (Figure 5) with Bayelsa State average inclusion. He wrote the original first draft of the manuscript, including Introduction, Literature Review, Methodology, Results, Discussion, Conceptual Narrative and Timeline, and incorporated supervisor corrections.

***Pere-Ere Glory Agbedi:* -** Pere-Ere Glory Agbedi was responsible for data curation, including extraction of routine immunization data from LGA immunization summary registers, ward tally sheets and DHIS2 electronic reports domiciled at Bayelsa State Primary Health Care Board, cleaning, outlier checks and computation of derived variables (coverage, zero-dose prevalence, gap, composite risk score). She participated in investigation through field follow-up with LGA Immunization Officers and Monitoring and Evaluation Officers for data completeness. She contributed to project administration, including coordination of ethical clearance application with reference number PHCB/AD/171/Vol.1/p.57 dated 15th March 2026, liaison with Executive Secretary, State Immunization Officer and State Cold Chain Store, and management of backup storage and data management folders. She provided supervision and guidance on operational feasibility of ward-level targeting in riverine context and interpretation of findings in light of Bayelsa Big Catch-Up rounds of 2024, 2025 and OOP Intensification of 2026. She contributed to visualization through review and correction of maps and charts for operational relevance, and contributed to writing through review, editing and drafting of portions of Discussion and Authors' Contributions sections. Both authors jointly reviewed and validated the final research-ready dataset with 100% completeness across 8 LGAs and 105 wards, jointly reviewed and approved the final manuscript for submission, and agreed to be accountable for all aspects of the work.

No Conflict of Interest

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