Spatio-temporal variations and determinants of antenatal care utilization among adolescents in Bulawayo metropolitan area, Zimbabwe: an analysis of routine data, 2019-2024

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Abstract

Adolescent pregnancy remains a major public health challenge in low- and middle-income countries, contributing to maternal and neonatal morbidity and mortality. Antenatal Care (ANC) mitigates pregnancy-related risks through timely screening, education, and skilled care. However, adolescent ANC utilization remains low – even in urban areas with numerous health service providers. While national demographic and health surveys are used to estimate ANC utilization rates in urban areas, they lack the spatial detail needed to reveal intra-urban disparities for local level health planning. We modelled spatial and temporal variations for at least one visit with a skilled provider (ANC1+) utilization among pregnant adolescents (10-19 years) within Bulawayo metropolitan province, Zimbabwe, 2019–2024. We extracted ANC utilization records from the District Health Information System and linked the data to a geocoded list of health facilities. Adolescent population denominators (pregnancies) were derived from three independent sources: WorldPop, national statistics agency and the US Census Bureau International Database (IDB). Health Facility Catchment Areas (HFCA) were estimated based on Thiessen polygons and linked with ANC use, pregnancies by population source and geospatial covariates (travel time to facilities, urbanization, maternal education, household wealth index, family planning, and vaccine coverage). A Bayesian spatial-temporal model was used to estimate ANC1+ coverage per HFCA by year and population. Provincial ANC1+ coverage ranged from 60.4% (WorldPop) to 70.6% (IDB) based on the population source. There was a high spatial heterogeneity in coverage across catchment areas, ranging from below 25% to over 80%. HFCAs located within core urban areas had higher coverage relative to the periphery. No clear temporal trend was observed. Higher wealth index and shorter travel time were significantly associated with ANC1+ utilization. The results are useful for local targeting of resources.

Introduction

Adolescent pregnancy – pregnancy in females under 20 years – remains a major global public health challenge, particularly in Low- and Middle-Income Countries (LMICs), contributing significantly to maternal and neonatal morbidity and mortality (Ganchimeg *et al.*, 2014; Kawakita *et al.*, 2016; Maheshwari *et al.*, 2016, 2022). Sub-Saharan Africa (SSA) has the highest adolescent pregnancy prevalence at 19.3% (Kassa *et al.*, 2018), with Zimbabwe having an adolescent pregnancy prevalence of 23.7%,

higher than the regional average (UNFPA *et al.*, 2023). Beyond the direct health risks, early pregnancy often leads to school dropout, limits future employment, and perpetuates intergenerational poverty (Kassa *et al.*, 2018; Maheshwari *et al.*, 2022). Timely, adequate Antenatal Care (ANC) can help mitigate some of these risks (Tekelab *et al.*, 2019; WHO, 2016).

ANC is defined as the care given to a woman during pregnancy with the primary aim of promoting and protecting the health of women and their unborn babies during pregnancy. It includes key components such as screening for risk identification, prevention and management of pregnancy-related or concurrent diseases, health education and promotion which improves outcomes for both mothers and newborns (WHO, 2016). However, adolescents, typically have lower ANC utilization than adults due to social stigma, limited autonomy and barriers in accessing adolescent-friendly services (Kawakita *et al.*, 2016; Banke-Thomas *et al*., 2017; Anaba *et al*., 2022). In SSA, one skilled ANC visit is associated with a 39% reduction in neonatal mortality (Tekelab *et al.*, 2019). ANC utilization is strongly associated with improved perinatal survival and better maternal outcomes (Graham *et al.*, 2006; Mcdonagh, 1996). ANC coverage is a key indicator of maternal health service utilization, measured through indicators such as ANC1+ (at least one visit with a skilled provider), ANC4+ (at least four visits under the old WHO model), and ANC8+ (eight recommended contacts under the 2016 WHO recommendations). Globally, ANC1+ coverage is high, but SSA has the lowest levels, averaging around 77% (Dickson *et al.*, 2022). Adolescents, face additional barriers, with lower coverage across all ANC indicators such as timely initiation of first ANC visit, receipt of vaccines (tetanus toxoid) and supplementation (folic acid and iron tablets) (Banke-Thomas *et al.*, 2017). In Zimbabwe, ANC1+ coverage is high nationally (93%) based on the most recent Demographic and Health Surveys (DHS) from 2024, but drops significantly for ANC4+ (75%) and ANC8+ (25%), with adolescent girls showing notably lower percentage of ANC utilisation across all indicators (ZIMSTAT, 2025).

In LMICs, ANC coverage is mainly estimated using population-based surveys such as the DHS and Multiple Indicator Cluster Survey (MICS) (Benova *et al.*, 2018). These surveys offer nationally representative estimates with well-defined denominator and detailed socio-demographic indicators collected as part of the surveys. However, they are conducted infrequently and lack spatial granularity needed for local health planning (Benova *et al*., 2018). Further, they are expensive and have limited sample size for subgroups (for example, pregnant adolescents) analysis within urban areas (Benova *et al.*, 2018; Maïga *et al.*, 2021). This reduces the utility of national surveys (DHS and MICS) in identifying local disparities (Silvestre, 2020; Maïga *et al.*, 2021). This has been exacerbated by the recent defunding of the DHS Program which threatens the tracking of health indicators in LMICs including SSA (Khaki *et al.*, 2025). On the other hand, Routine Health Information Systems (RHIS) offer an alternative, collecting facility-level data aggregated into platforms like the District Health Information System (DHIS2) (Silvestre, 2020; Maïga *et al.*, 2021; Byrne & Sæbø, 2022). RHIS provide continuous, timely and geographically disaggregated data for frequent monitoring and localized decision-making (Byrne & Sæbø, 2022). However, RHIS has data have low completeness in terms of health facility reporting rates, presence of outliers and some health facilities are often not part of national health management information system (Silvestre, 2020; Breakthrough RESEARCH, 2021; Byrne and Sæbø, 2022). Because RHIS data are collected at the health facility level, estimating denominators (for example for pregnant adolescents) in the corresponding health facility catchment area (HFCA) is challenging, particularly in settings with high population mobility, inaccurate population estimates and low healthcare utilization rates (Breakthrough RESEARCH, 2021; Byrne & Sæbø, 2022). In addition, RHIS data lack individual and household-level socio-demographic variables which constrains the ability to explore factors associated with service use (Silvestre, 2020; Maïga *et al.*, 2021; Byrne & Sæbø, 2022).

ANC coverage also varies across space due to differences in healthcare provision and utilization, climate, urbanization, and socio-economic and demographic factors (Macharia *et al.*, 2023b). Such factors include travel time to facility, maternal education, household wealth, exposure and access to health related information (Banke-Thomas *et al.*, 2017; Anaba *et al.*, 2022). Assessing the spatial variation of healthcare utilization indicators such as ANC within urban areas has received increasing research attention in recent years (Macharia *et al.*, 2023b, 2023d; Heyi *et al.*, 2025). Historically, urban populations have exhibited better health outcomes compared to rural ones, an effect attributed to better availability of healthcare services, improved transportation and communication systems and better socioeconomic conditions in urban areas (Macharia *et al.*, 2023b, 2023d; Adewuyi *et al.*, 2024). However, emerging evidence suggests a diminishing or even a reversal of this urban health advantage (Matthews *et al.*, 2010; Menashe-Oren & Masquelier, 2022; Norris *et al.*, 2022; Macharia *et al.*, 2023b; Santos *et al.*, 2024; Adewuyi *et al.*, 2024). In some of the cities, this trend has been linked to growing intra-urban inequities, the proliferation of informal settlements, overstretched urban health systems, persistent poverty and disparities in service quality and affordability. Further, rapid urbanization in SSA has intensified these challenges, often outpacing infrastructure and healthcare expansion and exacerbating disparities within cities (Amouzou *et al*., 2024; Faye *et al.*, 2024).

Bulawayo Metropolitan Province (Bulawayo), Zimbabwe's second-largest city, which serves as the administrative and economic hub of the Matabeleland region, has not been spared either. Rapid urban and peri-urban expansion has increased the demand for maternal healthcare. Infrastructure gaps hinder access to timely services, especially for vulnerable groups like pregnant adolescents (Sithole *et al.,* 2024). Long distances, poor transport, and limited facility coverage reduce ANC utilization (MoHCC, 2020; Sithole *et al.*, 2024). To address these problems, peripheral clinics conduct monthly outreach to more peri-urban settlements, aiming to extend services to populations far from static facilities. However, to date, DHS provides only national and provincial estimates of the proportion of adolescent girls classified as ANC1+ visit. DHS surveys are not powered to provide reliable provide estimates at the sub-national or city level such as for Bulawayo, because their sample sizes are designed for national and provincial representation rather than fine-scale geographic disaggregation. This lack of granular data hinders localised planning and targeted resource allocation.

Geospatial methods allow integration of RHIS with socio-demographic data derived from household surveys and other sources such satellite data, minimizing limitations of RHIS while enabling robust estimates at facility or fine sub-national levels (Eliott & Wartenberg, 2004). The geospatial techniques support the estimation of denominators (population at risk or the population in need of a given service such as ANC), facilitate linkage with socio-demographic variables and allow identification of spatial relation-

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ships to produce more accurate and reliable coverage estimates (Eliott & Wartenberg, 2004). Several studies have used geospatial techniques to examine disparities in maternal healthcare utilization within urban areas in SSA, including Dakar (Sy *et al*., 2024), Addis Ababa (Mekonnen *et al.*, 2024; Heyi *et al*., 2025), Lusaka (Jacobs *et al.*, 2024), Bamako (Traoré *et al*., 2024) and Dar es Salaam (Kagoye *et al.*, 2024). However, none of these studies address the unique challenges associated with analysing routine data - particularly for adolescent pregnancies - at the HFCA level. Such analyses require innovative approaches to derive accurate population denominators, as well as methods for smoothing estimates across space and time using geospatial covariates and accounting for spatial relatedness based on Tobler's first law of geography (1970) which holds that everything is related to everything else, but near things are more related than distant things (Tobler, 1970). Therefore, the objective of this paper is to estimate ANC1+ coverage among adolescents in Bulawayo, Zimbabwe, 2019–2024, based on routine data combined with high resolution geospatial covariates using spatial modelling approaches. Specifically, we aimed to: i) quantify spatial and temporal variations in ANC1+ coverage across HFCA; ii) examine the influence of key geospatial factors associated with adolescent ANC utilization; and iii) compare ANC1+ coverage estimates derived from three population data sources to assess how differences in population denominators affect coverage estimates.

Materials and Methods

Study setting and health service context

Bulawayo's urban health system presents a unique context for examining adolescent ANC coverage, characterized by relatively high service availability but variable affordability and access. This setting provides an opportunity to understand the dynamics of ANC coverage among adolescents within city environments in SSA. Zimbabwe is administratively divided into ten provinces (Figure 1), two of which are metropolitan provinces: Harare (the capital city) and Bulawayo. The latter, *i.e.* the study area, is administratively divided into three health districts (Northern Suburbs, Nkulumane and Emakhandeni) and 29 urban wards (Figure 1). Bulawayo metropolitan province comprises Bulawayo city and its surrounding peri-urban areas. It is the second largest city in terms of population and economic activity (Sithole et al., 2024). Bulawayo accounts for 4.4% of the country's population and about 10% of Zimbabwe's urban population. In 2022, the population was 668,000 with women constituting 51% of the total population, with a total fertility rate of 2.7.

The health service delivery system in Bulawayo has a two-tier structure, consisting of primary and secondary care levels. The former is made up of public health clinics run by Bulawayo municipality, community health workers, community-based distributors

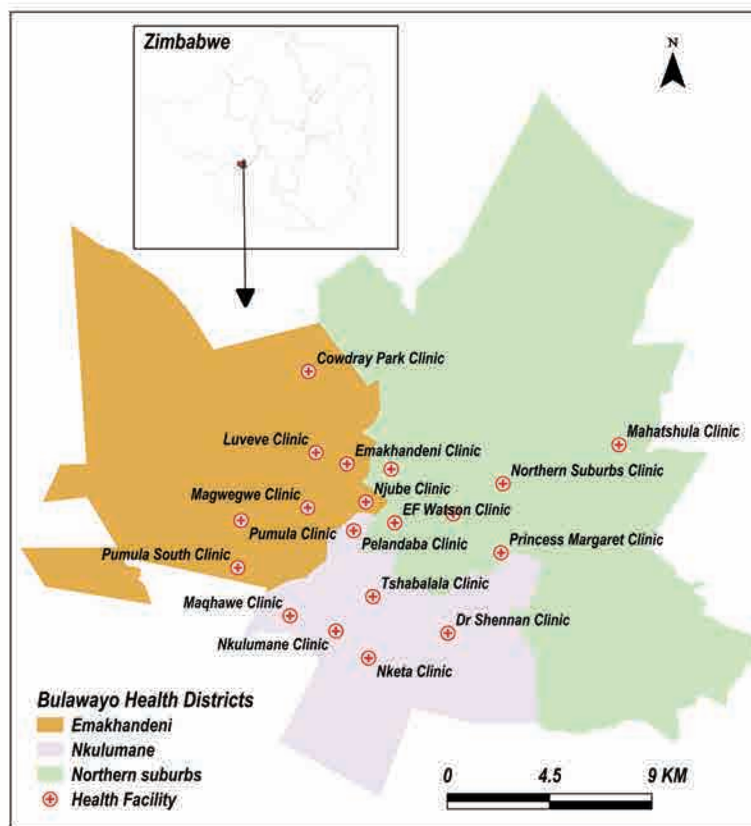

Figure 1. Bulawayo Metropolitan Province (study area) in Zimbabwe. The three health districts and 18 health facilities providing antenatal care services in the province are shown.

and private clinics; and the latter consisting of two central hospitals. ANC is handled at the primary care level with municipal clinics (public health facilities) providing the bulk of ANC services (MoHCC, 2021; Osika *et al.*, 2010).

Zimbabwe has implemented several laws, polices and strategies addressing adolescent sexual and reproductive over the past four decades (MoHCC, 2016, 2020, 2021). Following its independence in 1980, the country prioritized expanding access to education and healthcare with a focus on improving general reproductive health services and promoting gender equality in education. The Zimbabwe National Family Planning Council was established in 1985 to promote contraceptive use among the population, adolescents included (ZNFPC, 2025). In 2016, Zimbabwe aligned its national ANC guidelines with the updated WHO model recommending increasing the number of ANC contacts to eight from four. In addition, Zimbabwe has user fee exemption policy for pregnant women, children under five years and adults over 65 years; however, implementation has been inconsistent. Municipal clinics in urban areas, including Bulawayo continue to charge user fees to sustain daily operations (MoHCC, 2020; Cordaid Zimbabwe, 2024; Fichera *et al.*, 2024). These fees have created a financial barrier to accessing maternal and child health services in urban areas, particularly where external support from non-governmental organizations has been limited. To mitigate these challenges, an Urban Voucher Programme was introduced in 2014 in five wards of Nkulumane District in Bulawayo (Cordaid Zimbabwe, 2024; Fichera *et al*., 2024). This programme facilitated pregnant women coming from poor backgrounds to access pregnancy related health services free of charge at municipal clinics. The programme was scaled up to include all wards in Bulawayo in 2022 before ending in 2023 (Cordaid Zimbabwe, 2024).

Approach

To estimate adolescent ANC1+ coverage over time, six steps were undertaken (Figure 2). First, we assembled data on i) number of ANC1+ visits by adolescents, ii) geocoded list of health facilities in Bulawayo; iii) total population estimates; iv) pregnancy outcome multipliers (adolescent birth rates, miscarriage rates and stillbirths rates) from census and household surveys; and v) geospatial covariates reflecting accessibility and socio-demographic characteristics. These included travel time to the nearest health facility, Relative Wealth Index (RWI), urbanicity, maternal education, unmet need for family planning and DPT3 vaccine coverage – the latter serving as a proxy for the strength of the primary healthcare system. Second, we assessed the quality of ANC1+ visit data to ensure completeness, consistency, and reliability across reporting facilities. This involved checking for completeness and outliers in line with WHO data quality assessment guidelines. Third, we combined the female adolescent population estimates and the adolescent conversion parameters to derive the expected number of adolescent pregnancies and computed the crude ANC1+ coverage at the provincial and district level, for each of the six years. Fourth, we derived HFCA based on Voronoi polygons (Macharia *et al.*, 2023c; Johnson *et al.*, 2025). Fifth, we estimated the number of adolescent pregnancies per HFCA and derived the corresponding crude ANC1+ coverage at this level. In the final step (sixth), we applied geospatial modelling approaches (small area estimation approaches) to estimate ANC1+ coverage across HFCAs accounting for the identified geospatial covariates.

Data

Routine ANC1+ visits

The study utilised routine health data from DHIS2, a system that serves as the national health information repository where both public and private healthcare facilities report maternity statistics (Byrne & Sæbø, 2022). ANC visits reported by private health facilities are usually ascribed to the nearest public health facility within the same catchment area (MoHCC, 2020). The data from DHIS2 covered ANC1+ visits from January 2019 to December 2024 and were disaggregated by facility and grouped into five-year age bands, from 10–14 years up to 45–49 years. The ANC1+ visits were used to compute the primary outcome variable in this study (ANC1+ coverage among adolescents).

Geocoded list of health facility

A list of all 18 geocoded public municipal clinics (Figure 1) which offer ANC services in Bulawayo was obtained from Bulawayo medical directorate. The list contained facility name and geographical coordinates (Bulawayo City Council, 2025).

Population estimates

There are no existing estimates of pregnant adolescents from Zimbabwe National Statistics Agency (ZIMSTAT) at broad subnational units. Therefore, we calculated these estimates using population data from three sources ZIMSTAT, WorldPop, and the US Census Bureau International Database (IDB). WorldPop provided high spatial resolution data suitable for fine-scale mapping, while ZIMSTAT and the IDB supplied official and internationally comparable demographic estimates. The use of all three sources complemented each other due to biases associated with each source. Further, the three sources also facilitated for sensitivity analysis to evaluate how the choice of the population data influences ANC1+ coverage estimates.

Annual, high spatial resolution gridded population estimates at a 100 x 100 meter resolution between 2019 and 2024 for adolescents were obtained from WorldPop's Open Spatial Demographic Data and Research portal (WorldPop, 2025; Tatem, 2017). WorldPop produces population density maps disaggregated by age and sex for each 100m x 100m cell globally due to the limitations of census data. That is, census data are at coarse resolution (broad administrative units) and available only after 10 years. To deal with these limitations, WordPop uses dasymetric and machine learning techniques to redistribute census-based counts to high spatial resolution maps informed by covariates such as land cover and nighttime lights. Estimates are usually projected based on United Nations estimates (Tatem, 2017).

The second set of population data were obtained from the ZIMSTAT from the 2022 national census with population projections for 2019 to 2024. The MoHCC receives annual population projections from the ZIMSTAT office for use in health planning and resource allocation. While the national census provides data disaggregated down to the ward level (sub-national units), the annual population projections are only broken down by province, age group, and sex, but not by HFCA (Bhattacharya *et al*., 2019; Center for Global Development, 2025).

The third set of population estimates was from the IDB, which offers demographic projections and estimates for more than 200 countries and sub-national regions. It provides comprehensive population data by sex and single year of age, based on a combination of administrative records, surveys, and censuses, using the

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cohort-component projection method (U.S. Census Bureau, 2025). As with ZIMSTAT data, this set of data was not disaggregated to HFCA level.

Factors associated with adolescent ANC utilisation

As is common with routine health data, detailed covariates were not available as part of the routine data (Maïga *et al.*, 2021). Consequently, we focused on secondary geospatial covariates at high spatial resolution to explore factors potentially influencing ANC utilisation among adolescents. These variables were selected based on their theoretical relevance and data availability at high resolution. All the covariates were in a gridded format and were aggregated to HFCAs level, using of Zonal statistics tool in QGIS version 3.40.7. That is the mean value within each HFCA polygon was extracted to generate comparable area-level estimates for each covariates (Figure 3).

Travel time to health facilities

Longer travel times may reduce the likelihood of ANC attendance where women living further from health facilities are less likely to start ANC early, or attend multiple visits(Banke-Thomas et al., 2017). We proxied geographic access by modelled motorised travel time to the nearest health facility based a cost-distance model incorporating roads, terrain, and facility locations. The

Figure 2. Research methodology flowchart for computing ANC1+ coverage.

motorised travel time represents the most realistic and policy-relevant mode of transport for accessing health facilities in Bulawayo, where public transport and informal commuter systems are widely used. However, we note that younger adolescents might have specific care seeking behaviour not captured by this travel of scenario. The travel time surface was accessed from Child Poverty and Access to Services project at 100 m resolution for 2022 (Watmough *et al.*, 2022).

Relative Wealth Index (RWI)

Economic status affects ability to afford transport, health services, and opportunity costs – key for dependent adolescents (Banke-Thomas *et al.*, 2017). We used RWI, a deep learning-derived measure of household economic status based on de-identified connectivity data, satellite imagery, and other non-traditional sources (Chi *et al.*, 2022). Estimates at 2.4 km spatial resolution for year 2022 were available from the HDX portal (Chi *et al.*, 2022; Meta Data for Good, 2024).

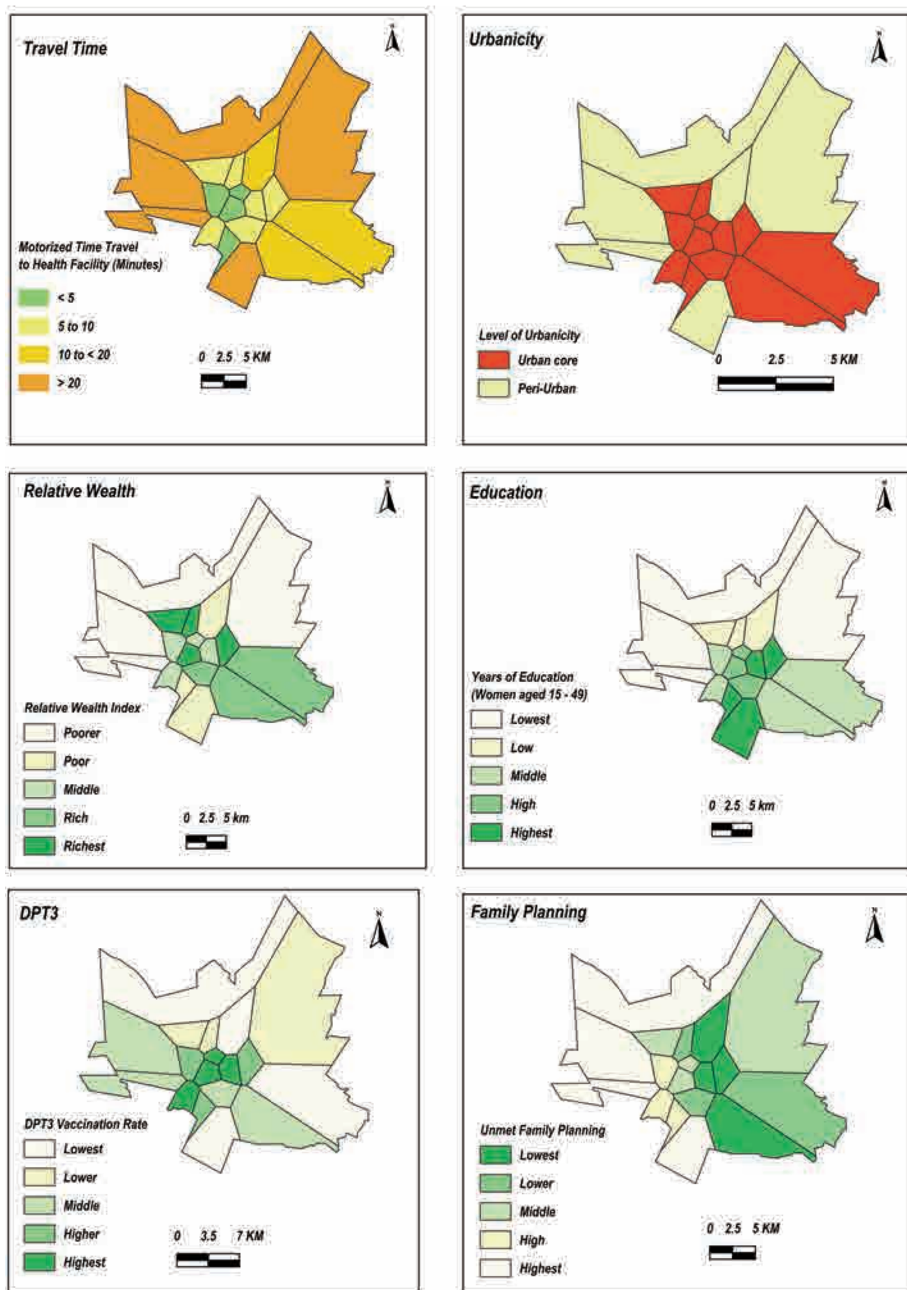

Figure 3. The spatial distributions of the geospatial factors used to estimate the spatial variation of antenatal care utilization aggregated at the health facility catchment area. Panels show travel time to health facilities (2022), Relative Wealth Index (2022), mean years of education for females aged 15-19 (2017), urbanicity levels (2020), unmet need for family planning (2015) and DPT3 coverage (2015) in Bulawayo Metropolitan Province, Zimbabwe.

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Maternal education

Higher education is linked to better health literacy, greater autonomy, and reduced stigma in accessing ANC (Banke-Thomas *et al.*, 2017).This was defined as the average years of education for females aged 15-49, modelled using Bayesian geostatistics (Local Burden of Disease Educational Attainment Collaborators, 2019) at 5km grids for the year 2017 and available from GHDx portal (IHME, 2017).

Urbanicity

Urban areas typically have better access to health services. It was defined using the Global Human Settlement Model (GHS-SMOD) 2020 classification, which applies the degree of urbanisation framework to a global 1 km² population and built-up grid. The dataset categorizes areas into classes such as urban centre, dense urban cluster, semi-dense urban cluster, suburban/peri-urban, rural cluster, low-density rural, and very low-density rural (Dijkstra *et al.*, 2021; Schiavina *et al.*, 2023).

Unmet need for family planning

It represents the proportion of women who want to delay or avoid pregnancy but are not using contraception. A high unmet need indicates barriers to reproductive autonomy, potentially leading to unintended adolescent pregnancies and late ANC initiation. The estimates were modelled from Zimbabwe DHS 2015 using Bayesian geostatistical methods to create a continuous surface at 5 km spatial resolution (Gething *et al.*, 2015). The data were available from the DHS Program spatial data repository (DHS Program, 2015).

DPT3 vaccine coverage

A proxy for strength of routine immunization and broader health system performance; requires repeated contact with healthcare system. High DPT3 coverage indicates stronger health infrastructure, which may also support better ANC service delivery for adolescents. Estimates modelled using Bayesian geostatistical methods from Zimbabwe DHS 2015 at 5 km spatial resolution (Gething *et al*., 2015) were available from the DHS Program spatial data repository (DHS Program, 2015).

Analysis

ANC data quality assessment

We examined the quality of DHIS2 ANC1+ data following the WHO Data Quality Assurance toolkit based on two measures: completeness and outliers. Completeness was assessed to identify facilities and periods for which there was missing data/reports. It was defined as the ratio of the number of reports received from a health facility to the total number of expected reports from that facility in a year. On the other hand, outliers defined as values exceeding two standard deviations (2Sd) from the mean for the ANC bookings were identified. Extreme outliers (greater than 3Sd) were removed and replaced with the median, based on reporting patterns and contextual review. The assessment was done in R version 4.4.1 (2024-06-14) statistical software.

Population data harmonisation and disaggregation

Among the three population datasets, only WorldPop provided spatially explicit data at a 100 m resolution, making it directly compatible with both district and HFCA boundaries via spatial overlays. In contrast, ZIMSTAT and IDB data were only available at the provincial level, necessitating proportional downscaling to estimate populations at finer spatial scales. Therefore, to disaggregate adolescent female population (ages 10–19) from ZIMSTAT and IDB to district and HFCA levels, the WorldPop data was used as a spatial weighting reference. This approach assumed that WorldPop's spatial distribution closely reflects actual distributions in ZIMSTAT and IDB data. To achieve this, we used annual totals adolescent females (2019–2024) from WorldPop data to estimate provincial, district and HFCA-level adolescent populations. A weighting factor for each district and HFCA was computed as a ratio between district/HFCA and the provincial total. This annual weighting factor was then applied to ZIMSTAT and IDB provincial totals to estimate district and HFCA-level adolescent females. The computations were done in QGIS version 3.40.7.

Estimating adolescent pregnancies (denominator)

Based on the computed number of adolescent females (from WorldPop, ZIMSTAT and IDB), we estimated the number of adolescent pregnancies requiring ANC. This conversion was facilitated by three parameters - Age-Specific Fertility Rates (ASFR), miscarriage rates and stillbirth rate - drawn from the 2024 ZDHS and the 2023 National Assessment on Adolescent Pregnancies in Zimbabwe (UNFPA *et al*., 2023).

For girls aged 10–14, age-specific birth rates were unavailable due to low fertility rates. Therefore, a fixed pregnancy rate of 1% (UNFPA *et al.*, 2023) was used to convert adolescent females to the number of adolescent pregnancies. For girls aged 15–19 years, an ASFR of 69 per 1,000 women was applied for adolescents aged 15-19. This was further adjusted for pregnancy losses using a miscarriage rate of 106 per 1,000 live births and a stillbirth rate of 13 per 1,000 births. Consequently, the total number of pregnant adolescent girls (10–19 years) was obtained by summing the estimated pregnancies in the 10–14 and 15–19 age groups per each population data source. This formed the denominator representing adolescents in need of ANC services in Bulawayo.

Health facility catchment areas

HFCA also known as a sphere of influence, tributary area, service area or demand field, represents a geographical area around a health facility describing the population that uses its services (Macharia *et al*., 2021, 2023c). While there were district boundaries, Bulawayo like most LMICs urban areas did not have pre-existing, systematically defined delineated HFCAs. Geospatial approaches offer practical and policy-relevant tools for defining HFCAs within health systems. Defining a representative and robust HFCA substantially depends on the availability of geo-positioned residential addresses of patients linked to a facility and robust data on their health-seeking behaviour (Macharia *et al.*, 2021). A variety of computational approaches can be employed in defining HFCAs, ranging from simple proximity-based models to complex models incorporating travel time, facility capacity, and population behaviour (Macharia *et al.*, 2023c; Johnson *et al*., 2025).

Despite their limitations, including the inability to account for transportation networks, terrain, facility bypassing, and individual preferences, Thiessen polygons (Macharia *et al.*, 2021; Johnson *et al.,* 2025) were applied as a pragmatic approach. They offer a simple and replicable method that the MoHCC feasibly use in routine programming to delineate preliminary catchment areas where offi-

cial boundaries are unavailable. Therefore, we used the Thiessen polygons approach to model HFCA for each of 18 health facilities (Figure 1). This approach delineates a region that incorporates all points that are closer to a given facility than any other. It partitioned the entirety of the study area such that each space is assigned to the nearest health facility, approximating a facility's area of influence (Macharia *et al.*, 2021, 2023c). This was achieved by using the Voronoi Polygon tool in QGIS version 3.40.7 with the input as the geographic coordinates of all 18 health facilities. The modelled HFCA are shown in Figure 3 layered with the maps of geospatial covariates.

ANC1+ crude coverage

The annual crude ANC1+ coverage was estimated at two levels (district-level and HFCA) between 2019 and 2024 (based on three population sources after downscaling) as the ratio between ANC1+ visits and number of pregnant adolescents. At the district level, paired sample t-tests were used to test whether the coverage estimates were significantly different based on the population denominator used.

Modelling ANC1+ coverage

Small Area Estimation (SAE) (Moraga, 2019) was used to model ANC1+ coverage among pregnant adolescents across Bulawayo between 2019 and 2024. This approach was selected for its ability to generate stable and reliable estimates in small geographic areas – such as HFCAs where routine data often are sparse or inconsistently reported. SAE models incorporate spatial dependence, allowing estimates in data-sparse areas to be improved by borrowing strength from neighbouring units in addition to covariates. Specifically, a Bayesian hierarchical spatio-temporal model was fitted at the HFCA level to estimate adolescent ANC1+ coverage from 2019 to 2024. The model adjusted for geospatial covariates and accounted for both spatial and temporal structure in the routine data. Compared to crude estimation, this approach provides improved accuracy by incorporating prior knowledge and generating uncertainty estimates.

Let $Y(i, t) = Y_t(i)$ denote ANC1+ coverage for HFCA I (where i = 1......18) and year t = 1......6(2019 – 2024). The model was defined as:

$$y_t(i) = \alpha_0 + X(i)'\beta + \theta(i)' + \gamma_t + \varphi_t + \delta_{i,t} \qquad \text{Eq. 1}$$

where γ_t is a structured temporal random effect following a random walk in time of first order (RW1) accounting for structured gradual year-to-year trends temporal variation over the study period); φ_t the unstructured temporal random effect modelled as identically distributed random error (iid) ; $\delta_{i,t}$ a space-time interaction component to allow spatial patterns to vary across years. A Type 1 spatio-temporal interaction which assumes two unstructured effects (space and time) was chosen for parsimony due to identifiability concerns with highly structured interactions; α_0 the intercept; and X a vector of geospatial covariates associated with ANC1+; β the corresponding regression coefficients of the covariates (fixed effects); Before the geospatial covariates were included in the SAE model, a series of univariate linear regression models were conducted to identify factors associated with adolescent ANC1+ coverage in addition to multicollinearity assessment using Variance Inflation Factors (VIFs). $\theta(i)'$ is a spatial random effect comprising of two parts a spatial structured random effect (μi) to account for unmeasured spatial risk factors for ANC1+ use and unstructured random effect (vi) to account for area-specific characteristics and local noise. These two components were accounted for by the Besag-York-Mollié (BYM) conditional autoregressive modelling CAR model (Besag *et al.*, 1991; Bernardinelli *et al.*, 1995). The spatial dependence (vi) was represented through a neighbourhood matrix defining a set of adjacent neighbours for each HFCA and modelled through a CAR process. That is, parameters in one HFCA were influenced by the average of the neighbouring HFCAs. Two HFCAs were defined as neighbours if they shared either a boundary or a node (queen adjacency). The unstructured component was modelled as an iid with a normal

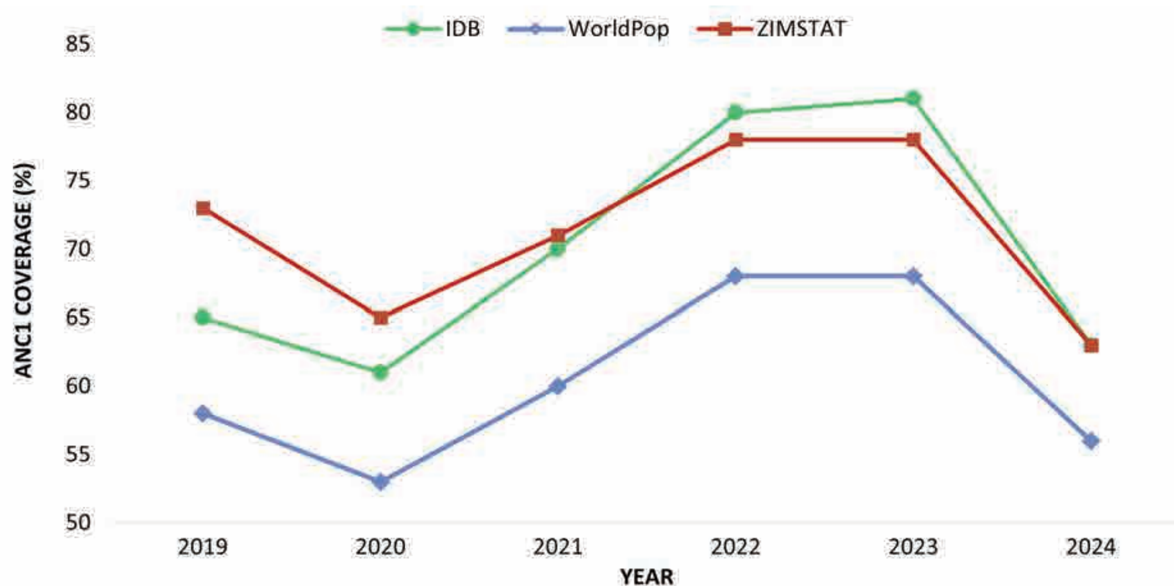

Figure 4. Temporal trends of adolescent ANC1+ coverage by the population denominator, 2019-2024 in Bulawayo Metropolitan Province, Zimbabwe.

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distribution. Model implementation was carried out using the Integrated Nested Laplace Approximation (INLA) framework in R (version 4.4.1). The generated annual ANC1+ coverage estimates for pregnant adolescents at the HFCA level across Bulawayo and were used to assess local patterns and trends during the study period.

Validation

A 20% subset of data at HFCA level was used for validation using three statistics. The Pearson's correlation coefficient was used to assess the agreement between predicted and observed coverage at HFCA level. The residuals were then used to assesses the overall model performance and bias through the Root Mean Square Error (RMSE) and Mean Square Error (MSE) respectively.

Results

Data quality assessment

The overall reporting rate for the 18 HFCAs level over the six years in Bulawayo was 98%, above the WHO threshold (90%). The reporting completeness was variable across the years ranging from 93% to 100%. The lower rates were observed in 2019 and 2020 before improving from 2021 (93%) to 2024 (100%). On the other hand, facility-level data completeness was generally high but varied slightly. Out of all 18 facilities, 13 (72%) achieved 100% completeness, while the lowest reporting rate was 97%. All facilities surpassed the WHO 90% threshold for completeness. There was no facility with extreme outliers (> 3Sd from the mean), while moderate outliers (>2Sd from the mean) ranged from 2.8 % to 3.7 %. Only one clinic had more than 1 moderate outlier (2) in a calendar year (2021).

Adolescent pregnancies in Bulawayo

Depending on the source of the base population data, The annual average number of adolescent pregnancies (ages 10–19) in Bulawayo ranged between 3,592 to 3,708 (Table 1). Over the six years, 21,860 adolescent pregnancies were recorded but varied depending on source, with WorldPop (24,216) having the highest and ZIMSTAT (20,532) the lowest.

ANC1+ crude coverage

At the provincial level, ANC1+ coverage estimates also varied depending on the population denominator used. Between 2019 and 2024, ZIMSTAT and IDB produced consistently higher coverage estimates compared to WorldPop, with overall provincial means of 71.3% (ZIMSTAT), 70.6% (IDB) and 60.4% (WorldPop). While coverage increased steadily across all three data sources between 2020 and 2022/2023, a decline was observed in 2024 (Figure 4). There were no statistically significant differences between ZIMSTAT and IDB provincial estimates (p=0.6973). In contrast, WorldPop-based estimates were significantly lower than those based on both ZIMSTAT (p<0.001) and IDB (p<0.001).

As seen at higher administrative levels, ANC1+ coverage varied across the three districts. Nkulumane recorded the highest average coverage between 2019 and 2024, while the northern suburbs consistently showed the lowest levels. Northern suburbs and Emakhandeni districts experienced a decline in coverage between 2019 and 2021, followed by an increase in 2022/2023, and a subsequent decline in 2024. Nkulumane, on the other hand, showed a different trend – coverage declined from 2019 to 2020, rose in 2021 and then gradually declined from 2022 through 2024 (Figure 5). These trends were consistent regardless of the population denominator used. Coverage estimates also differed by data source across districts. ZIMSTAT and IDB were closely aligned with minimal variation. WorldPop, however, consistently reported lower overage, with the largest differences observed in Emakhandeni and

Table 1. Estimated number of adolescent pregnancies (ages 10-19) in Bulawayo Metropolitan Province in Zimbabwe 2019-2024.

Source	2019	2020	2021	2022	2023	2024	Total
ZIMSTAT	3,312	3,348	3,408	3,480	3,480	3,504	20,532
WorldPop	4,128	4,140	4,068	4,020	3,948	3,912	24,216
IDB	3,684	3,588	3,492	3,384	3,348	3,336	20,832
Average	3,708	3,692	3,656	3,628	3,592	3,584	21,860

ZIMSTAT, Zimbabwe National Statistics Agency; WorldPop; Open Spatial Demographic Data and Research; IDB, US Census Bureau International Database.

Table 2. Coefficients showing the association between covariates and ANC1+ coverage.

Predictor	Coefficient (β) and 95% CI	p
Travel Time to health facility	-0.34 (−0.65 to −0.02)	0.037*
Relative Wealth Index (RWI)	21.41 (6.61 to 36.22)	0.005*
Urbanicity	-1.11 (−2.622 to 0.40)	0.153*
Education	10.20 (−17.02 to 37.43)	0.464
Unmet need for family planning	218.25 (−182.04 to 618.54)	0.288
DPT3 Coverage	143.47 (10.68 to 276.26)	0.037*

Based on univariate models based on the ZIMSTAT population data (denominator).

Nkulumane, where estimates were approximately 11-12 percentage points lower compared to those from ZIMSTAT.

Factors associated with ANC1+ utilization

We tested six variables in bivariate models. Based on a significance threshold of $p<0.2$, four variables were selected for subsequent modelling: RWI; travel time to the nearest facility; DPT3 vaccination coverage; and urbanicity (Table 2). Variance Inflation Factor (VIF) was used to assess multicollinearity. Apart from urbanicity that had a VIF of 6.4, the variables had values below the commonly accepted threshold of 5: 3.01 for travel time, 2.42 for RWI, and 1.42 for DPT3 coverage. Due to this high collinearity, urbanicity was excluded from the final model, so the analysis using Bayesian hierarchical model continued with only the other three predictors. From all the three fitted Bayesian hierarchical models using WorldPop, ZIMSTAT and IDB population datasets, increasing travel time to the nearest health facility was associated with lower ANC1+ coverage among adolescents (Table 3 and Figure 6).

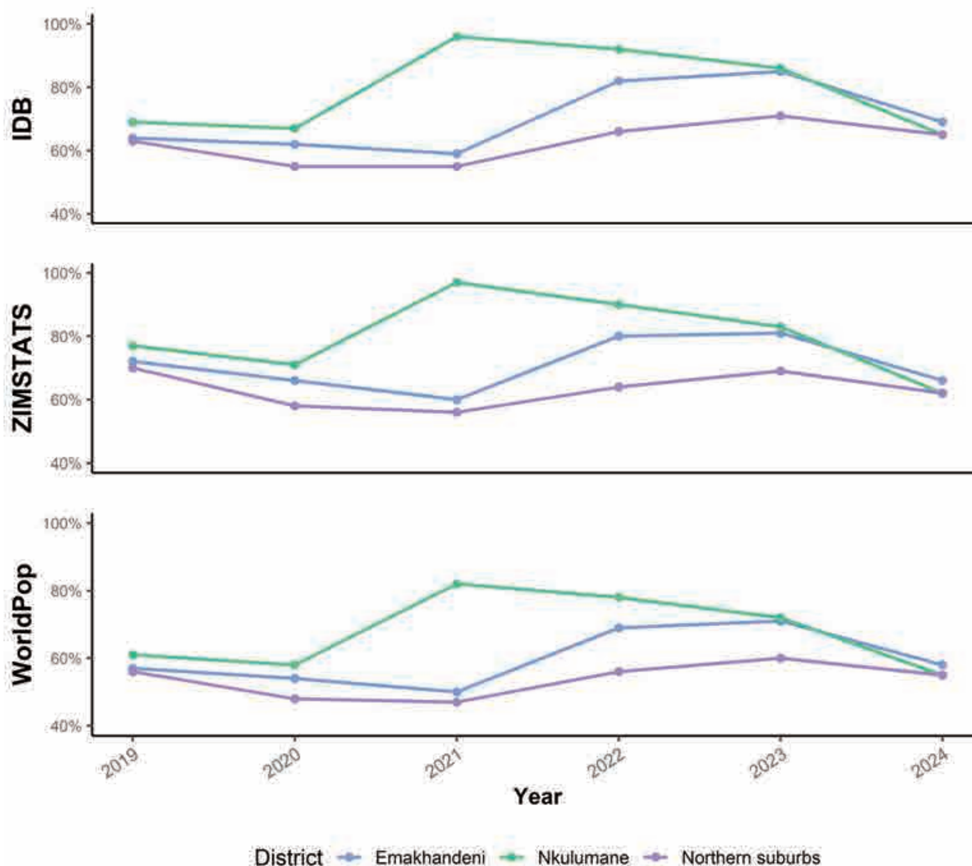

Figure 5. Temporal variation of adolescent ANC1+ by year, district and population, 2019 -2024 in Bulawayo Metropolitan Province, Zimbabwe.

Table 3. Fixed effects from spatio-temporal models of ANC1+ coverage among pregnant adolescents in Bulawayo Metropolitan Province.

Variable	WorldPop Value (CI)	ZIMSTAT Value (CI)	IDB Value (CI)
Travel time			
< 5 minutes (Ref)	-	-	-
5-10 minutes	−0.845 (−1.90, 0.20)	−1.989 (−3.63, -0.40)	−1.24 (−2.53, 0.03)
10-20 minutes	−1.73 (−3.15, -0.32)	−2.95 (−5.10, -0.84)	−2.18 (−3.89, -0.48)
>20 minutes	−0.82 (−2.05, 0.41)	−1.415 (−3.26, 0.42)	−1.03 (−2.51, 0.45)
Relative Wealth Index			
Poor (Ref)	-	-	-
Rich	0.82 (−0.10, 1.74)	1.67 (0.29, 3.09)	1.15 (0.03, 2.26)
DPT3 Coverage			
High (Ref)	-	-	-
Low	0.44 (−0.52, 1.42)	0.47 (−0.97, 1.93)	0.49 (−0.68, 1.66)

Population, denominator; VI, credible interval; IDB, US Census Bureau International Database.

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The effect was strongest and statistically significant for travel times between 10–20 minutes. Areas with less travel time (5-10 minutes) were also negatively associated with ANC1+ coverage, reaching statistical significance in the ZIMSTAT model. Adolescents in areas classified as relatively wealthy had higher ANC1+ coverage compared to those in poorer areas, with significant associations observed in the ZIMSTAT and IDB models. No significant association was found between DPT3 coverage and ANC1+ utilisation in any of the models (Table 3 and Figure 6).

Model selection and validation

Overall, the ZIMSTAT model provided the best fit with the lowest deviance information criterion (DIC), with all models showing the importance of geographic access and socioeconomic status in adolescent ANC1+ coverage. Model validation showed a strong correlation (r=0.905) between predicted and observed adolescent ANC1+utilisation rates. The RMSE was 0.098, indicating a good fit between the data and the model, while a low MSE (0.01) confirmed minimal bias in the model's predictions.

Modelled ANC1+ coverage

Figure 7 shows the modelled mean adolescent ANC1+ coverage per HFCA by year (2019-2024) and population source. Across all three data sources, coverage levels varied geographically and temporally. An overall improvement in ANC1+ coverage was observed from 2020 to 2022, particularly in the northern and central HFCAs, followed by a decline in 2024. Heterogeneity in coverage was evident throughout the study period, with the Dr Shennan HFCA consistently showing lower predicted coverage (<25%) across all years and data sources. HFCAs predominantly located in the northern and western regions of the city had low coverage compared to centrally located HFCAs. In contrast, Nkulumane Clinic and Pelandaba Clinic demonstrated high coverage levels, exceeding 100% between 2021 and 2022 (crude coverage). There were improvements in adolescent ANC1+ coverages between 2022 and 2023, noticeable in the IDB and ZIMSTAT data. Despite these overall gains, spatial disparities persisted. Coverage estimates based on IDB and ZIMSTAT showed broadly similar spatial patterns. In contrast, WorldPop-based estimates display persistently lower coverage across most HFCAs, with fewer areas reaching the highest coverage categories. This discrepancy reflects the influence of the underlying population denominators used in the estimation process.

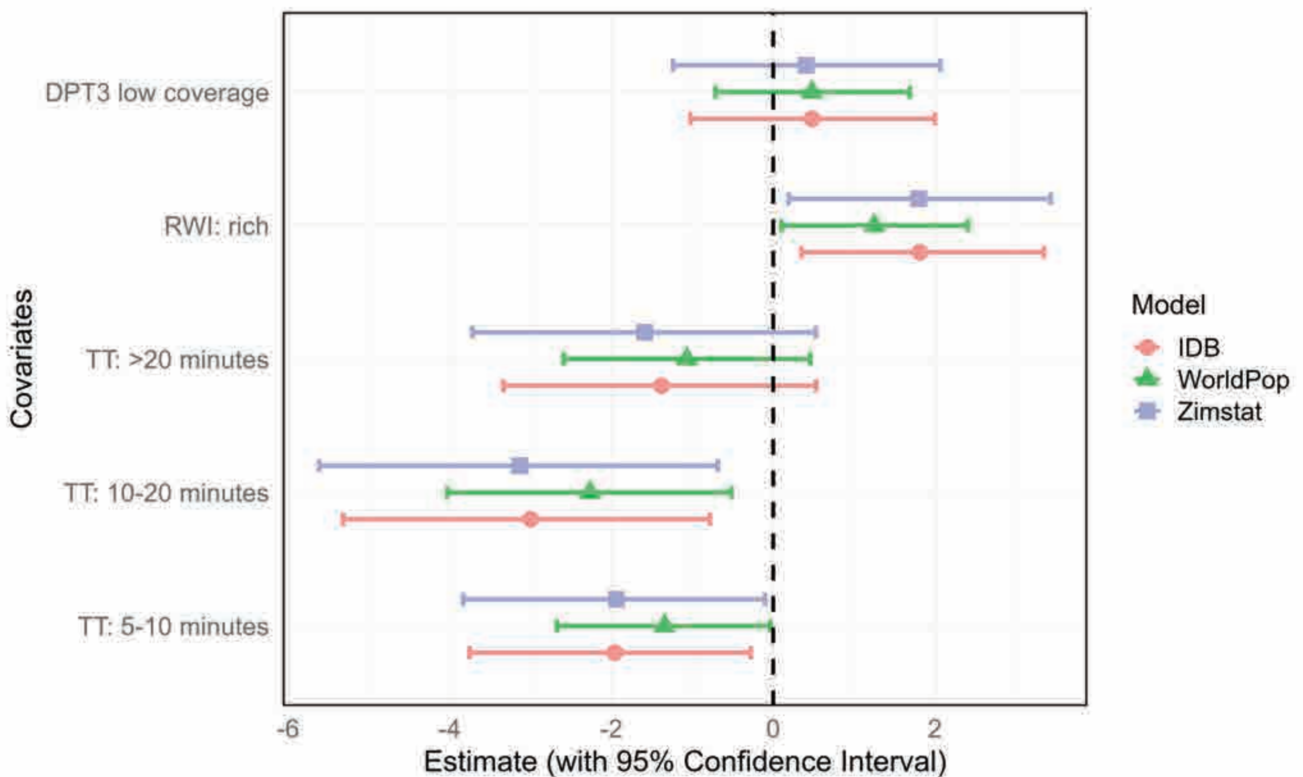

Figure 6. Graphical representation of coefficients from the SAE model showing the association between covariates and ANC1+ in Bulawayo Metropolitan Province, Zimbabwe.

Discussion

Our study applied geospatial models to examine spatial and temporal variations in ANC1+ coverage and its determinants among pregnant adolescents in Bulawayo metropolitan province from 2019 to 2024, using routine health data. Overall, the completeness and the quality of routine data was high and met the WHO's 90% threshold. At the provincial level, the coverage of ANC1+ showed that about seven in ten pregnant adolescents used ANC services over the six-year period. However, the utilization varied by year, by district and HFCA and depended on the source of population data. These pronounced intra-urban differences highlight the need for granular, data driven analyses to better identify and support adolescents in need of healthcare services such as ANC.

Compared with the national estimates from the 2024 ZDHS, the lower adolescent ANC1+ coverage observed in this study reflects broader challenges in measuring adolescent maternal health in urban contexts. The small adolescent sample size in the ZDHS and ZDHS's lack of sub-district detail limit comparability and highlight the value of using routine health data for urban targeting (Janocha *et al.*, 2021). Moreover, the 2024 ZDHS has shown that despite high national ANC coverage, adolescents are less likely than older women to receive comprehensive ANC services (ZIMSTAT, 2024). These differences underscore the need for adolescent-responsive health systems that go beyond mere service availability (Baird *et al.*, 2025; Banke-Thomas *et al.*, 2017).

Temporal fluctuations in ANC1+ coverage corresponded with broader health system disruptions during the COVID-19 pandemic, which constrained service delivery and health-seeking behaviour (Amnesty International, 2020; Shakespeare *et al.*, 2021; Kassa *et al.*, 2024). The service disruptions during this period have been widely documented across SSA (Kassa *et al.*, 2024), with Zimbabwe reporting notable declines in maternal and reproductive health indicators during lockdowns (Amnesty International, 2020; Shakespeare *et al.*, 2021). This likely contributed to the reduced service uptake and provision among adolescents. Recovery between 2022 and 2023 reflects partly the reactivation of outreach activities and voucher-based interventions targeting urban women (Kassa *et al.*, 2024).

Likely influenced by the early introduction of the Urban Voucher Programme (UVP) in 2014 (Fichera *et al*., 2024), Nkulumane District consistently recorded the highest coverage across the study period. The UVP, which subsidise maternal services for low-income women, was initially implemented in five Nkulumane wards and later expanded to include all clinics in Bulawayo in 2022 (World Bank, 2019; Fichera *et al*., 2024). Following this expansion, there was an apparent levelling of ANC1+ coverage between districts, which indicates that benefits may diffuse as access barriers are progressively reduced across the

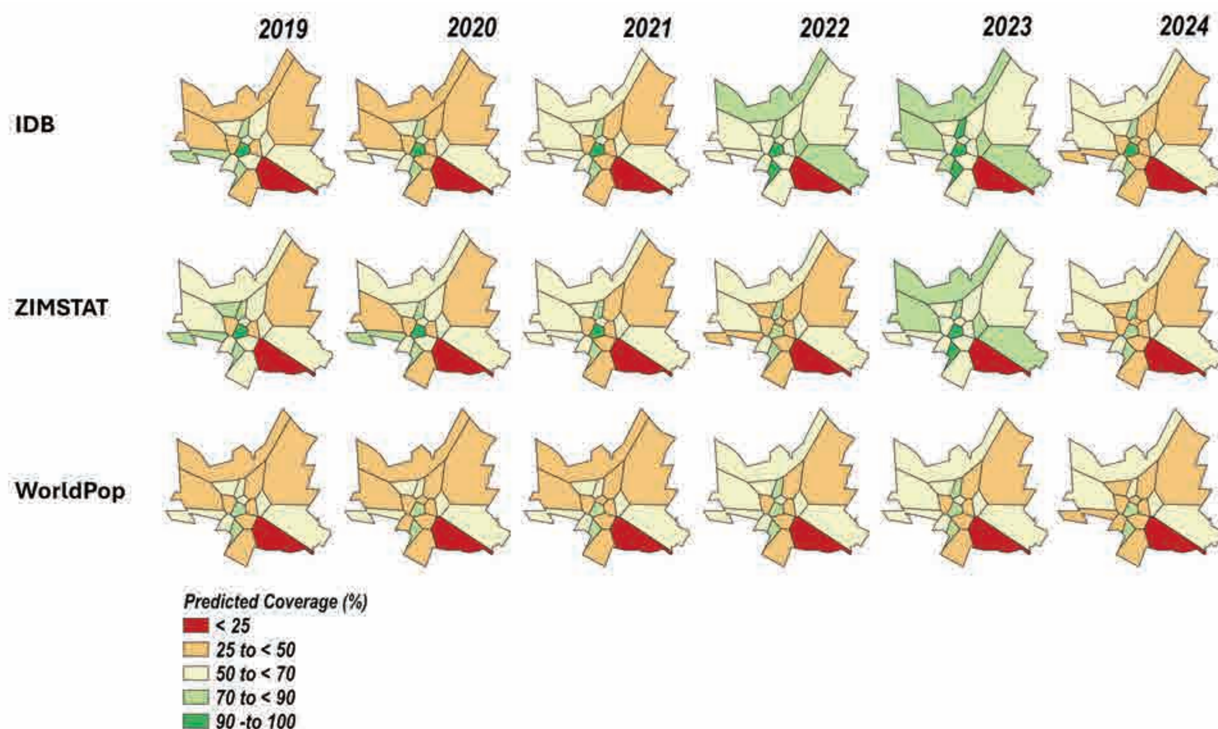

Figure 7. Modelled adolescent ANC1+ coverage by catchment area and population source 2019 - 2024 in Bulawayo Metropolitan Province, Zimbabwe.

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city (World Bank, 2019; Cordaid Zimbabwe, 2024; Fichera *et al.*, 2024). These findings align with previous work showing that voucher schemes and performance-based financing can positively impact maternal health equity and service uptake (Powell-Jackson *et al.*, 2015). However, this temporal association should not be interpreted as causality as observed programme effects may be influenced by other concurrent health system interventions, policy shifts, and other external contextual factors (Tanser *et al.*, 2006).

While district level estimates may be useful for broad level comparisons, robust estimates are required for targeted planning at the local level (Johnson *et al.*, 2025). At this level, coverage of adolescent ANC1+ was highly heterogeneous in both space and time. Facilities in densely populated, centrally located neighbourhoods (Nkulumane, Pelandaba, and Emakhandeni) attracted higher adolescent utilization, which is likely due to physical accessibility, perceived service quality and cross-catchment movement. Financial incentives and perceived service quality attract users from beyond formal catchment boundaries leading to cross-catchment client flow, a pattern observed in other settings implementing subsidy programmes (Tanser *et al.*, 2006; World Bank, 2019; Tessema *et al.*, 2021; Fichera *et al.*, 2024). In contrast, persistently low coverage at the Dr. Shennan Clinic suggests that geographic location, transport links, and social factors substantially shape adolescents' service choices. Similar patterns of "facility bypassing" have been reported in studies from Kenya and Ghana where convenience and confidentiality strongly influence adolescent care-seeking behaviour (Escamilla *et al.*, 2018; Amoro *et al.*, 2021).

The most consistent finding was a negative association between travel time and adolescent ANC1+ utilization across the three models, suggesting that travel times poses a key access barrier. However, travel time estimates are heavily dependent on model assumptions which is important in urban areas where factors such as traffic congestion and time of day can affect estimates of travel time (Macharia *et al.*, 2023a, 2024). However, these were not captured by the secondary data that we used. Incorporating actual care-seeking behaviour of pregnant adolescents, likely requiring observational studies or use of big data, would improve estimates (Njogu *et al.*, 2025). High relative wealth in the community was positively associated with ANC1+ utilization in all models, with the strongest and most precise effects observed in the ZIMSTAT based model. The strength of the primary healthcare system, as reflected by DPT3 coverage, did not show a statistically significant association with ANC1+ utilization in any model.

The choice and source of population data (the denominator) are critical in coverage analyses (Hierink *et al*., 2022). By using three different population estimates we generated a plausible range for ANC1+ coverage, which helps to account for uncertainty in adolescent population counts. This is key as many previous analyses rely on a single denominator and do not provide such checks and balances. The models assessing association yielded broadly consistent effect directions, but ZIMSTAT data produced stronger and more statistically robust estimates, which may be due to its better alignment with administrative boundaries and facility catchment areas. Conversely, WorldPop and IDB models, while fitting slightly better statistically, may over-smooth population variation due to their gridded or modelled nature. These discrepancies reflect differences in the underlying population estimation methodologies and have implications for interpreting adolescent ANC coverage and planning corresponding health services.

Beyond geospatial covariates and model structure, systemic barriers to adolescent ANC uptake remain important. These include stigma, negative provider attitudes, and the absence of adolescent-friendly services, which have been widely reported in other SSA cities (Chandra-Mouli *et al.*, 2019). Such barriers may explain low utilisation in facilities like the Dr. Shennan one and warrant further investigation using, for example, mixed methods approaches. Bulawayo presents a complex urban health system characterised by population mobility and facility bypassing, both of which complicate catchment-level service delivery metrics. For example, coverage rates exceeding 100% as seen in Bulawayo can occur in urban contexts where adolescents travel beyond their catchment area to access preferred facilities, particularly when multiple clinics are within reaching leading to small catchments. A crude coverage exceeding 100% may also result from inaccuracies in the population denominators and data reporting errors such as double counting and over reporting. Incentives such as targeted financing schemes, perceived service quality, or outreach activities can further encourage clients to bypass the nearest facility, leading to numerators that exceed the local population denominator (Powell-Jackson *et al*., 2015; Gao *et al.*, 2020). This phenomena of recording coverage exceeding 100% is not unique to Bulawayo, it has been reported in other SSA countries (Dunkle *et al.*, 2014; Agiraembabazi *et al.*, 2021; Maïga *et al.*, 2021; Ngo-Bebe *et al.*, 2025). Despite these complexities, the routine data in Bulawayo were stable and reliable in line with previous findings (Farnham *et al.*, 2023), aligning with national performance benchmarks. Data completeness consistently met WHO benchmarks, likely due to the country's structured health information management protocols, which include mandatory timelines and validation checks across all levels. This contrasts with other countries in the region where routine data completeness remains a challenge, such as South Africa's Eastern Cape (74.6%) or Malawi's sub-national reporting (<85%) (Aron *et al*., 2024; Thabethe & Mathews, 2024).

Policy implications

The findings highlight four key recommendations to improve adolescent ANC1+ coverage and equity in service delivery. First, the MoHCC should define official health facility catchment areas and maintain updated, age-disaggregated population denominators to support accurate coverage estimation and targeted resource allocation. Second, Bulawayo's strong routine data systems should be sustained and could be complemented by institutionalising the use of geospatial analysis in routine data reviews. Third, a qualitative study is recommended to explore persistently low ANC1+ coverage in some of the health facilities to guide the development of targeted, context-specific interventions. Finally, while this study did not directly evaluate outreach coverage, the observed spatial heterogeneity in ANC1+ uptake suggests that that monitoring service reach in distant urban areas may help identify underserved adolescent for focused outreach activities.

Strengths and limitations

We highlight the value of routine data combined with geospatial modelling in producing actionable, locally relevant estimates for adolescent ANC1+ coverage. Our findings reveal spatial and temporal differences in service utilization that are not captured by national averages, emphasizing the need for disaggregated planning. While the overall approach used to generate catchments is replicable and easy to adopt for the Ministry of Health, however, Voronoi polygons do not account for actual travel routes or physical barriers which may misrepresent actual service use especially in urban areas. We likely underestimated ANC1+ coverage in

peripheral HFCAs and overestimated in the central ones. The lack of disaggregated population data from the MoHCC necessitated reliance on WorldPop estimates, which may not fully capture local adolescent demographics. Additionally, access to high-quality spatial and temporally matching covariates was limited, this potentially reducing the precision of the geospatial models and the ability to fully explain the coverage differences. Finally, because private facilities data are reported through public facilities, it is unclear how much each facility contributes, which may reduce the accuracy of catchment-level coverage estimates.

Conclusions

Within the Bulawayo Metropolitan Province, there was notable spatial variation in ANC1+ utilization among pregnant adolescents, with differences observed between health facility catchment areas. The findings underscore the importance of intra-urban analyses in understanding maternal health service utilization and need for targeted, equity-focused interventions in urban settings.

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