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Geographical inequalities and factors associated with emergency obstetric and newborn care readiness in Ethiopia: a national Bayesian spatial analysis

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Research Article

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Abstract

Background

Maternal and neonatal survival depends not only on access to health facilities but also on the capacity of those facilities to provide timely, high-quality emergency obstetric and newborn care (EmONC). Despite substantial investments in maternal and newborn health and expansion of emergency obstetric services in Ethiopia, persistent gaps in facility readiness continue to limit the delivery of life-saving care. Previous national studies have largely focused on service availability or individual readiness components, with limited assessment of multidimensional emergency readiness and its geographical variation. We developed a Comprehensive Emergency Readiness Index (CERI) and assessed its national distribution, geographical variation, inequality, and facility-level factors associated with emergency obstetric and newborn care readiness using nationally representative health facility data from Ethiopia.

Methods

We conducted a nationally representative cross-sectional study using data from 776 health facilities included in the 2021 Ethiopia Service Provision Assessment. A latent Comprehensive Emergency Readiness Index (CERI) was constructed from essential emergency obstetric and newborn care medicines, equipment, and clinical guidelines using structural equation modelling. National estimates accounted for facility sampling weights. Geographic variation was examined using spatial autocorrelation analyses, and Bayesian hierarchical spatial regression models based on the stochastic partial differential equation approach with integrated nested Laplace approximation were fitted to evaluate associations between facility characteristics and emergency readiness. Model performance was compared using the deviance information criterion, widely applicable information criterion, conditional predictive ordinates, and predictive accuracy measures.

Results

The nationally weighted mean CERI was 57.4 (SE 2.6), compared with an unweighted mean of 70.6 (SD 36.0). CERI varied substantially across regions, ranging from 27.8 (95% CI 15.9–39.6) in Addis Ababa to 62.5 (50.9–74.1) in Amhara, with moderate national inequality (Gini coefficient 0.374; coefficient of variation 0.510). General hospitals demonstrated the highest readiness (89.1, 95% CI 86.0–92.2), whereas medium clinics had the lowest (5.6, 95% CI 1.3–9.9). Government-managed facilities had higher readiness (78.5, 95% CI 75.0–82.0) than private-for-profit facilities (10.5, 95% CI 5.2–15.9). The Bayesian hierarchical spatial model incorporating both regional and spatial random effects provided the best overall model fit (DIC 2516.49). After accounting for spatial dependence and regional heterogeneity, greater provider availability (posterior mean 4.64, 95% CrI 1.02–8.27) and oxytocin availability (posterior mean 9.96, 95% CrI 7.52–12.40) were positively associated with CERI, whereas medium clinics had substantially lower CERI than the reference facility category (posterior mean − 55.37, 95% CrI − 70.09 to

− 40.61). Residual spatial autocorrelation was no longer evident after model adjustment (Moran's I − 0.013; *P* = 0.770).

Conclusion

Emergency obstetric and newborn care readiness remains unevenly distributed across Ethiopian health facilities, with substantial geographical and facility-level variation and moderate national inequality. Provider availability, oxytocin availability, and medium clinic status were independently associated with the Comprehensive Emergency Readiness Index after accounting for spatial dependence and regional heterogeneity. Integrating multidimensional readiness assessment with spatially informed health-system monitoring could support more equitable assessment and prioritisation of emergency obstetric and newborn care readiness within Ethiopia's health system.

Introduction

Maternal and neonatal survival depends not only on access to health facilities but also on the capacity of those facilities to provide timely, high-quality emergency obstetric and newborn care (EmONC). Evidence indicates that improvements in service utilization alone are insufficient when facilities are unable to deliver the interventions required to manage life-threatening obstetric and neonatal complications. Consequently, strengthening facility readiness has become central to achieving global maternal and newborn survival targets (1).

National facility assessments, including the Ethiopia Service Provision Assessment, have consistently documented deficiencies in essential medicines, equipment, trained personnel and clinical guidelines, indicating that improvements in service availability have not been accompanied by comparable improvements in facility readiness. These gaps remain important barriers to Ethiopia's health-sector transformation agenda, universal health coverage and Sustainable Development Goal 3 (2).

Previous investigations have substantially advanced understanding of emergency obstetric and newborn care (EmONC) readiness in Ethiopia; however, important methodological and analytical gaps remain. National analyses based on the 2021–2022 Ethiopia Service Provision Assessment have primarily described the availability and geographical distribution of EmONC signal functions and service coverage, providing valuable evidence on infrastructure and service availability but offering limited assessment of overall facility readiness or the determinants of geographical heterogeneity (3). Similarly, studies evaluating childbirth service readiness have compared alternative readiness indices derived from WHO Service Availability and Readiness Assessment (SARA), Service Provision Assessment (SPA), and WHO quality-of-care frameworks, demonstrating that conventional additive indices often fail to capture the multidimensional nature of facility readiness and may inadequately discriminate between facilities with different levels of service capacity (4). Other Ethiopian studies have focused on specific components of maternal or newborn care readiness, hospital preparedness, or spatial accessibility to EmONC services, rather than integrating structural resources, human capacity, and essential commodities into a single

nationally representative readiness construct while simultaneously accounting for spatial dependence (5). Consequently, important questions remain regarding whether observed regional differences reflect measurable facility characteristics, unobserved regional variation, or residual spatial processes that extend beyond administrative boundaries.

Despite increasing availability of nationally representative health facility data, important evidence gaps remain in understanding how emergency obstetric and newborn care readiness varies across Ethiopia after simultaneously accounting for facility characteristics, administrative heterogeneity, and underlying spatial dependence. Distinguishing these sources of variation is important because interventions addressing facility resources may differ from those required to address geographically clustered health-system constraints. Bayesian hierarchical spatial modelling provides a robust framework for partitioning observed and unobserved sources of variation while quantifying residual spatial patterns and associated uncertainty, thereby supporting geographically targeted decision-making and more efficient allocation of limited health-system resources. Therefore, this study developed a Comprehensive Emergency Readiness Index (CERI) and applied Bayesian hierarchical spatial modelling to examine its national distribution, geographical variation, inequality and facility-level factors associated with emergency obstetric and newborn care readiness using nationally representative data from the 2021–2022 Ethiopia Service Provision Assessment.

Materials and Methods

Study design

This study employed a nationally representative cross-sectional analytical design using secondary data from the 2021–2022 Ethiopia Service Provision Assessment (SPA). The study aimed to quantify comprehensive emergency obstetric readiness across health facilities providing childbirth services, examine geographical variation in readiness, and identify facility-level factors associated with emergency readiness using Bayesian spatial hierarchical modelling.

Because the SPA is a nationally representative health facility survey conducted using standardized sampling procedures, the study provides nationally generalizable estimates of emergency readiness among facilities providing maternal health services in Ethiopia.

Data Source

This study used data from the 2021–2022 Ethiopia Service Provision Assessment (SPA) conducted by the Ethiopian Public Health Institute (EPHI) in collaboration with the Ministry of Health and the DHS Program. The SPA is a nationally representative health facility survey designed to assess service availability and readiness across public and private health facilities in Ethiopia using standardized instruments developed under the Demographic and Health Survey (DHS) Program.

The SPA collected information through four complementary survey components, including the health facility inventory questionnaire, health worker interviews, client observations, and client exit interviews. The present study used the facility inventory and provider interview datasets because these modules contain detailed information on facility infrastructure, availability of essential medicines and equipment, provider characteristics, and emergency obstetric service readiness.

Facility geographic coordinates supplied by the DHS Program were subsequently linked to administrative boundary shapefiles for spatial analyses while preserving facility confidentiality through the standard DHS geographic displacement procedures.

Study Setting

The study was conducted in Ethiopia, the second most populous country in Africa, where maternal mortality remains a major public health challenge despite substantial expansion of institutional delivery services during recent decades. Ethiopia's health system consists of a three-tier service delivery structure comprising primary health care units, general hospitals, and specialized referral hospitals, delivered through public, private, faith-based, and other governmental providers.

The SPA survey covered health facilities distributed across all administrative regions of Ethiopia. Following data quality assessment and application of survey weights, facilities providing delivery services and possessing complete information on study variables were included in the present analysis. For cartographic visualization only, Sidama was displayed together with the former Southern Nations, Nationalities and Peoples' Region (SNNPR) because the corresponding GADM version used for mapping did not contain an independent Sidama administrative polygon. This visualization decision did not affect either the descriptive estimates or Bayesian statistical analyses, in which Sidama was analysed as an independent administrative region.

Study population and eligibility criteria

The source population consisted of all health facilities included in the Ethiopia SPA survey. The analytical population comprised facilities providing childbirth-related services with complete information on emergency obstetric readiness indicators, provider characteristics, facility characteristics, and survey design variables.

Facilities with zero sampling weights were excluded because they do not contribute to nationally representative estimates under the SPA sampling framework. Provider-level information was aggregated to the facility level before merging with facility inventory data, resulting in a single analytical dataset in which each observation represented one health facility.

After applying these eligibility criteria, the final analytical dataset included **776 health facilities** distributed across Ethiopia.

Sampling design and survey weighting

The Ethiopia Service Provision Assessment employed a nationally representative stratified sampling design to select health facilities providing health services across Ethiopia. The sampling frame was developed from the national master list of health facilities maintained by the Ministry of Health and incorporated stratification by facility type, managing authority, and geographical region to ensure national representativeness. Each sampled facility was assigned a survey sampling weight reflecting its probability of selection together with adjustments for non-response, following the standard DHS Service Provision Assessment methodology.

To obtain nationally representative descriptive estimates, all descriptive analyses incorporated the facility sampling weights supplied within the SPA dataset (variable **v005**). Sampling weights were rescaled by dividing the original six-digit integer weights by 1,000,000 to generate normalized probability weights before analysis. Facilities with zero sampling weights were excluded because they do not contribute to nationally representative inference under the SPA sampling framework.

Provider interview data were first aggregated to the facility level before linkage with the facility inventory dataset. Consequently, the health facility rather than the individual provider constituted the analytical unit throughout the study. All weighted descriptive statistics, including national means, proportions, regional estimates, and corresponding 95% confidence intervals, were calculated using survey design-based estimation procedures that accounted for the complex sampling design of the SPA.

To preserve the national representativeness of the Ethiopia Service Provision Assessment, facility sampling weights supplied by the survey were incorporated throughout the descriptive analyses using design-based survey estimation. During Bayesian spatial modelling, normalized facility sampling weights were included as probability weights in the likelihood contribution for each facility. This model-based approach accounts for unequal sampling probabilities while simultaneously estimating spatial dependence through hierarchical Bayesian inference. Because fully design-based Bayesian spatial models remain computationally challenging for large geostatistical analyses, this approach represents a widely adopted compromise for nationally representative health surveys analysed using the Integrated Nested Laplace Approximation framework and has been applied in recent Bayesian analyses of demographic and health survey data. The primary objective was therefore to obtain nationally representative parameter estimates while appropriately modelling residual spatial correlation.

Outcome construction: Comprehensive Emergency Readiness Index (CERI)

The primary outcome was the Comprehensive Emergency Readiness Index **(CERI)**, a continuous facility-level measure developed to quantify overall emergency obstetric readiness. The index was constructed from the Ethiopia Service Provision Assessment facility inventory using objectively observed indicators

representing the immediate availability of essential medicines, equipment, and clinical guidance required for the provision of emergency obstetric care.

Indicator selection was guided by the emergency obstetric readiness domains recommended within the World Health Organization Service Availability and Readiness Assessment **(SARA)** framework and the Demographic and Health Survey Service Provision Assessment **(SPA)** methodology. Candidate indicators were restricted to variables representing resources that were directly observed by trained SPA survey teams during facility assessment rather than self-reported by facility staff. This approach minimized reporting bias and ensured consistency across facilities.

Seven binary indicators were retained for construction of the latent readiness measure: availability of injectable oxytocin, magnesium sulfate, injectable antibiotics, and misoprostol; availability of functional suction equipment; availability of neonatal resuscitation equipment (bag and mask); and availability of emergency obstetric clinical guidelines. These indicators represent core components of emergency obstetric readiness that are routinely assessed within internationally standardized health facility assessment programmes.

Rather than assigning equal importance to each indicator, the study estimated a latent emergency readiness construct using structural equation modelling (SEM). The SEM specified a single latent factor representing comprehensive emergency readiness, with the seven observed indicators serving as reflective measures of the underlying construct. This model allows each indicator to contribute according to its empirical relationship with the latent readiness dimension while accounting for measurement error, thereby reducing potential bias associated with simple additive indices.

Following estimation of the latent factor model, facility-specific latent readiness scores were predicted using empirical Bayes estimation. To improve interpretability and facilitate comparison across health facilities, predicted latent scores were linearly rescaled to a standardized metric ranging from **0 to 100**, where higher values indicate greater comprehensive emergency readiness. This standardized measure constituted the Comprehensive Emergency Readiness Index (CERI) and was subsequently analysed as a continuous outcome throughout the descriptive, inequality, and Bayesian spatial analyses.

Because CERI was derived from directly observed facility resources rather than administrative reports or provider self-assessment, it provides an integrated measure of operational emergency readiness while preserving the multidimensional nature of facility preparedness for emergency obstetric care.

Construction of explanatory variables

Facility-level explanatory variables were selected to represent human resources, essential medicine availability, organizational characteristics, and health system ownership that may influence emergency obstetric readiness. Variables were obtained from the provider interview and facility inventory components of the Ethiopia Service Provision Assessment and were harmonized before analysis at the health facility level.

Human resource capacity was characterized using two facility-level indicators derived from the provider interview dataset. First, the total number of skilled maternity care providers was calculated by aggregating providers working within each facility who belonged to cadres directly involved in maternal and newborn care. Skilled providers included physicians, specialist physicians, nurses, midwives, nurse practitioners, and health officers, identified using standardized provider cadre classifications recorded in the SPA survey. Provider interview records were aggregated to the facility level using the unique SPA facility identification number. Facility-level totals were obtained by summing all eligible skilled providers within each facility, whereas the proportion of trained providers was calculated as the facility-specific mean of the binary EmONC training indicator among skilled providers.

A second human resource indicator represented the proportion of skilled providers trained in emergency obstetric and newborn care (EmONC). Among eligible skilled providers, recent EmONC training was identified using SPA variables documenting participation in training related to emergency obstetric care, including management of postpartum haemorrhage, neonatal resuscitation, administration of magnesium sulfate, and other core emergency obstetric interventions. For each health facility, the proportion of skilled providers reporting at least one qualifying EmONC training activity was calculated by dividing the number of trained providers by the total number of skilled providers.

Availability of injectable oxytocin was included as an indicator of essential medicine readiness. This variable was derived from the facility inventory using direct observation by SPA survey teams and was coded as a binary indicator indicating whether injectable oxytocin was available on the day of the facility assessment.

Facility organizational characteristics were obtained directly from the SPA facility inventory. Facility type was categorized according to the national health system classification as general hospitals, primary hospitals, referral hospitals, health centres, and medium clinics. Managing authority was classified as government or public facilities, private for-profit facilities, faith-based or mission non-profit facilities, and other governmental facilities, including military and federal police health institutions.

Provider-level variables were aggregated before linkage with the facility inventory dataset using the unique SPA facility identification number, ensuring that each observation in the final analytical dataset represented a single health facility. All explanatory variables were subsequently incorporated into both descriptive analyses and Bayesian hierarchical spatial models.

Data management

Data management was undertaken using Stata version 17 before statistical analyses were performed in R version 4.5.3 The provider interview dataset and the facility inventory dataset were independently processed before being integrated into a single facility-level analytical database.

Statistical analysis

Descriptive analysis

The analytical dataset consisted of all eligible health facilities with complete information on the Comprehensive Emergency Readiness Index (CERI), survey weights, provider characteristics, and facility readiness indicators. Descriptive analyses accounted for the complex sampling design of the Ethiopia Service Provision Assessment using facility sampling weights supplied with the survey. Weighted means and 95% confidence intervals (CIs) were estimated for continuous variables using Taylor series linearization, whereas weighted proportions with corresponding 95% CIs were estimated for binary variables. National summaries were additionally stratified by administrative region, facility type, and managing authority to characterize geographical and institutional variation in emergency readiness.

To quantify national inequality in emergency readiness, three complementary summary measures were calculated. The Gini coefficient quantified overall inequality in the distribution of CERI scores, the coefficient of variation measured relative dispersion around the national mean, and the interquartile range summarized variability within the middle 50% of facilities. These measures provided descriptive evidence of heterogeneity before formal spatial modelling.

Continuous explanatory variables were standardized to z-scores before inferential modelling to facilitate comparison of posterior regression coefficients and to improve numerical stability during Bayesian estimation.

Spatial autocorrelation analysis

Before fitting spatial models, global spatial dependence of CERI scores was assessed using Moran's I statistic. Health facilities were connected through an eight-nearest-neighbour spatial weights matrix, with row-standardized weights to account for unequal neighbourhood sizes. Statistical significance was evaluated using randomization-based inference.

Local Indicators of Spatial Association (Local Moran's I) were subsequently estimated to identify localized clusters of unusually high or low emergency readiness across Ethiopia. These exploratory analyses determined whether residual spatial dependence justified explicit spatial modelling.

Bayesian hierarchical spatial modelling

Because CERI is a continuous readiness score ranging from 0 to 100, Bayesian hierarchical Gaussian regression models were fitted using the Integrated Nested Laplace Approximation (INLA). Four progressively more complex models were specified to evaluate the contribution of observed covariates, regional heterogeneity, and latent spatial dependence.

Model A included only fixed effects representing provider availability, provider training, oxytocin availability, facility type, and managing authority.

Model B extended Model A by incorporating an independently and identically distributed (IID) regional random intercept to account for unmeasured heterogeneity among Ethiopia's first administrative regions.

Model C replaced the regional random effect with a continuous spatial random field using the stochastic partial differential equation (SPDE) approach. This model was intended to evaluate whether continuous geographic dependence alone adequately explained unexplained variability after adjustment for observed facility characteristics.

The final model (Model D) simultaneously incorporated fixed effects, regional random effects, and the latent spatial random field, thereby accounting for both administrative clustering and continuous spatial dependence.

The final model can be written as

$$\varvec{Y}_i = \beta_0 + \sum_{k=1}^{p} \beta_k X_{ik} + u_{r(i)} + \omega(s_i) + \epsilon_i,$$

Where

- $\varvec{Y}_i$ denotes the Comprehensive Emergency Readiness Index for facility i,
- $\varvec{\beta}_0$ represents the overall intercept,
- $\varvec{X}_{ik}$ denotes the observed facility-level covariates,
- $\varvec{u}_{r(i)}$ is the region-specific random intercept for administrative region r,
- $\varvec{\omega}(s_i)$ denotes the latent continuously varying spatial process evaluated at geographical location s_i,
- $\varvec{\epsilon}_i \sim N\left(0, \delta^2\right)$ represents Gaussian residual variation.

The latent spatial process $\omega(s)$ was approximated using the stochastic partial differential equation representation of the Matérn Gaussian random field.

SPDE mesh construction

The continuous spatial field was represented using a finite-element triangular mesh covering the entire Ethiopian national boundary. Administrative boundaries were obtained from the GADM database and projected into Universal Transverse Mercator Zone 37N (EPSG:32637) before mesh construction.

The mesh was constrained to the Ethiopian national boundary using boundary polygons to prevent interpolation outside the study area. Mesh resolution was selected to balance computational efficiency and spatial accuracy using

- maximum triangle edge lengths of 40 km within densely sampled areas,
- 100 km in peripheral regions,
- an 8 km minimum point separation (cutoff),
- inner and outer mesh extensions of 15 km and 50 km, respectively.

Projection matrices linking observed facility locations to mesh vertices were then constructed using linear finite-element basis functions. These specifications follow recommendations from Lindgren et al. (2015) and the current R-INLA SPDE implementation (6).

Prior specification

Weakly informative penalized complexity (PC) priors were specified for all random effects to reduce overfitting while allowing sufficient model flexibility.

For the SPDE model,

$$P\left(\rho\ <150km\right)=0.5,$$

was specified for the spatial range parameter, reflecting moderate prior belief regarding the distance over which facility readiness remains spatially correlated.

For the marginal standard deviation,

$$P\left(\delta\ >15\right)=0.05,$$

was specified, providing conservative shrinkage toward spatial homogeneity while allowing substantial residual variability when supported by the data.

Regional random effects were assigned penalized complexity priors on the precision parameter,

$$PC\ Prior\left(1,\ 0.01\right),$$

which encourages shrinkage toward zero unless regional heterogeneity is supported by the observed data.

Model comparison and selection

Competing models were evaluated using several complementary Bayesian model adequacy criteria. Model fit was assessed using the Deviance Information Criterion (DIC), Widely Applicable Information Criterion (WAIC), and the logarithm of the marginal likelihood. Predictive performance was additionally evaluated using Conditional Predictive Ordinate (CPO), root mean squared error, mean absolute error, and the coefficient of determination.

The model demonstrating the lowest DIC and WAIC together with superior predictive accuracy was selected as the primary inferential model.

Parameter estimation was based on posterior marginal distributions obtained through Integrated Nested Laplace Approximation, with uncertainty summarized using posterior means, 95% Bayesian credible intervals, and posterior probabilities of direction.

Software

All statistical analyses were conducted in R version 4.4 using the *INLA, survey, sf, spdep, terra, ggplot2, Matrix, and tableone* packages. Data management was undertaken in Stata 18 before spatial analyses were performed in R. Bayesian inference was conducted using the Integrated Nested Laplace Approximation implemented through the R-INLA framework.

Results

National distribution of the Comprehensive Emergency Readiness Index

A total of 776 health facilities were included in the analysis. The unweighted mean Comprehensive Emergency Readiness Index (CERI) was 70.6 (SD 36.0), compared with a nationally weighted mean of 57.4 (SE 2.6). Facilities had a weighted mean of 6.2 health-care providers (SE 0.2), and the weighted mean proportion of trained providers was 2.1% (SE 0.003). Oxytocin was available in an estimated 56.0% (95% CI 49.6–62.2) of facilities **(**Table 1**).**

The median CERI was 86.1 (IQR 31.5), with scores ranging from 0 to 100 **(**Table 2**)**. The median CERI was 86.1, with an interquartile range of 31.5. Scores ranged from 0 to 100, with a standard deviation of 36.0. The distribution was negatively skewed (skewness = − 1.18) **(**Fig. 1**).**

Table 1
National survey-weighted and unweighted characteristics of health facility emergency readiness, Ethiopia Service Provision Assessment 2021 (n = 776)

Characteristic	**Unweighted estimate**	**Survey-weighted estimate**
Comprehensive Emergency Readiness Index (CERI)	70.6 (36.0)	57.4 (SE 2.6)
Total providers	8.8 (4.1)	6.2 (SE 0.2)
Proportion of trained providers	0.046 (0.09)	0.021 (SE 0.003)
Facilities with oxytocin available	69.0%	56.0% (95% CI 49.6–62.2)

Table 2
National distribution and inequality of the Comprehensive Emergency Readiness Index

Statistic	Value
Mean	70.6
Median	86.1
Standard deviation	36.0
Skewness	−1.18
Gini coefficient	0.374
Coefficient of variation	0.510

Geographic variation in emergency readiness

Substantial regional variation in facility readiness was observed across Ethiopia (Table 3; Figs. 2–3). Readiness was highest in Amhara and Oromia and lowest in Addis Ababa and Harari, with intermediate values across the remaining regions.

Table 3
Survey-weighted regional Comprehensive Emergency Readiness Index

Region	Mean CERI	95% CI
Amhara	62.5	50.9–74.1
Oromia	61.8	52.8–70.9
S.N.N. P	59.5	47.8–71.2
Sidama	59.0	49.9–68.0
Dire Dawa	57.4	40.1–74.6
Somali	57.4	47.6–67.2
Benishangul	56.0	37.2–74.9
Afar	48.3	35.2–61.4
Gambella	46.6	29.5–63.6
Harari	39.3	22.7–55.9
Addis Ababa	27.8	15.9–39.6

Inequality in emergency readiness

Marked inequality in emergency readiness was observed across Ethiopian health facilities (Fig. 4). The Gini coefficient was 0.374, indicating moderate inequality in the national distribution of readiness scores. The coefficient of variation was 0.510, demonstrating considerable dispersion in readiness across facilities (Table 2).

Facility-level variation in emergency readiness

Emergency readiness differed substantially according to facility type (Table 4). General hospitals demonstrated the highest readiness, followed by referral hospitals and primary hospitals. Health centres had a mean readiness score of 79.4 (95% CI 76.5–82.2), whereas medium clinics demonstrated markedly lower readiness, with a mean CERI of 5.6 (95% CI 1.3–9.9) (Table 4). Government facilities demonstrated the highest mean CERI, whereas NGO-managed facilities had substantially lower readiness. Private-for-profit facilities exhibited the lowest readiness.

Table 4
Survey-weighted Comprehensive Emergency Readiness Index (CERI) by health facility type in Ethiopia

Facility type	Mean CERI	95% CI
General hospital	89.1	86.0–92.2
Referral hospital	87.7	80.2–95.2
Primary hospital	87.0	82.4–91.6
Health centre	79.4	76.5–82.2
Medium clinic	5.6	1.3–9.9

Table 5 shows substantial variation in CERI by managing authority. Government/public facilities had the highest mean CERI (78.5; 95% CI: 75.0–82.0), while private-for-profit facilities had the lowest (10.5; 95% CI: 5.2–15.9).

Table 5
Survey-weighted Comprehensive Emergency Readiness Index according to managing authority

Managing authority	Mean CERI	95% CI
Government/Public	78.5	75.0–82.0
Other governmental	62.1	20.3–103.9
NGO (Mission/Faith-based)	26.5	7.5–45.5
Private for profit	10.5	5.2–15.9

Model comparison and selection

Table 6 summarizes the comparative performance of the four Bayesian hierarchical models. Incorporating spatial dependence substantially improved model fit relative to models that ignored spatial structure. Both spatial models (Models C and D) achieved markedly lower DIC and WAIC values than Models A and B, indicating superior explanatory performance.

Model D produced the lowest DIC (2516.49), while maintaining predictive accuracy comparable to Model C (RMSE: 15.45 vs 15.43; MAE: 10.21 vs 10.22; R^2: 0.816 vs 0.817). Model D showed the best overall performance and was selected as the final model because it simultaneously accounted for spatial dependence and regional heterogeneity while maintaining predictive performance comparable to Model C.

Table 6. Comparison of Bayesian hierarchical spatial models for the Comprehensive Emergency Readiness Index (CERI)

Model	Specification	DIC	WAIC	RMSE	MAE	R^2
A	Fixed effects only	2533.66	2530.23	16.37	11.00	0.794
B	Fixed effects + regional random effect	2533.45	2529.69	16.37	11.00	0.794
C	Fixed effects + spatial random effect (SPDE)	2516.77	**2510.54**	**15.43**	10.22	**0.817**
D	Fixed effects + regional random effect + spatial random effect (SPDE)	**2516.49**	2511.58	15.45	**10.21**	0.816

Abbreviations: DIC, Deviance Information Criterion; WAIC, Watanabe–Akaike Information Criterion; RMSE, Root Mean Squared Error; MAE, Mean Absolute Error; R^2, coefficient of determination.

Spatial autocorrelation analysis

Table 7 summarizes the global spatial autocorrelation before and after Bayesian spatial modelling. Significant positive spatial autocorrelation was observed in the unadjusted outcome (Moran's I = 0.138, expected I = −0.001, $P < 0.001$), indicating significant spatial clustering.

Following adjustment using the Bayesian hierarchical spatial model, no evidence of residual spatial autocorrelation remained (Moran's I = −0.013, expected I = −0.001, $P = 0.770$), indicating no residual spatial autocorrelation after model adjustment.

Table 7. Global Moran's I statistics before and after Bayesian spatial modelling

Analysis	Moran's I	Expected I	P value
Observed CERI	**0.138**	−0.001	**<0.001**
Residuals from Model D	**−0.013**	−0.001	**0.770**

Bayesian hierarchical regression analysis

Table 8 presents posterior estimates from the final Bayesian hierarchical spatial model (Model D). After accounting for spatial dependence and regional-level heterogeneity, facility provider density and oxytocin availability remained positively associated with the Comprehensive Emergency Readiness Index (CERI). Specifically, a one-standard-deviation increase in the total number of providers was associated with a 4.64-unit increase in CERI (95% CrI: 1.02 to 8.27), with a posterior probability of 0.994. Likewise, a one-standard-deviation increase in oxytocin availability was associated with a 9.96-unit increase in CERI (95% CrI: 7.52 to 12.40), with a posterior probability exceeding 0.999.

Among facility characteristics, medium clinics exhibited substantially lower CERI values than the reference facility category (posterior mean: −55.37; 95% CrI: −70.09 to −40.61; posterior probability >0.999). No associations were observed for the proportion of trained providers, other facility types, or managing authority because their 95% credible intervals included the null value.

Table 8. Posterior estimates from the final Bayesian hierarchical spatial model (Model D) for Comprehensive emergency Readiness index (CERI)

Covariate	Posterior mean	Posterior SD	95% CrI	Posterior probability†
Intercept	40.71	16.12	9.09 to 72.32	0.994
Total providers (standardized)	**4.64**	1.85	**1.02 to 8.27**	**0.994**
Proportion of trained providers (standardized)	0.36	1.43	−2.45 to 3.18	0.600
Oxytocin availability (standardized)	**9.96**	1.24	**7.52 to 12.40**	**>0.999**
Health centre‡	−2.79	6.38	−15.29 to 9.73	0.671
Medium clinic‡	**−55.37**	7.51	**−70.09 to −40.61**	**>0.999**
Primary hospital‡	−2.12	6.96	−15.75 to 11.54	0.621
Referral hospital‡	−4.88	12.21	−28.81 to 19.09	0.657
NGO / Mission facility‡	−4.01	8.05	−19.80 to 11.78	0.692
Other governmental facility‡	−2.78	18.29	−38.63 to 33.13	0.562
Private for-profit facility‡	−2.37	5.36	−12.90 to 8.14	0.672

Spatial random effects and hyperparameter estimates

Table 9 presents posterior estimates of the spatial hyperparameters from the final Bayesian hierarchical model. The posterior mean spatial range was 175,953 m (95% CrI 48,807–510,829 m). The posterior precision of the regional random effect was 34.41 (95% CI: 8.74–85.65).

Table 9. Posterior estimates of spatial hyperparameters from the final Bayesian hierarchical model

Hyperparameter	Posterior mean	Posterior SD	95% CI
Gaussian observation precision	0.004	0.000	0.003–0.005
Regional precision	34.41	20.25	8.74–85.65
Spatial range (m)	175,952.88	125,677.29	48,807.41–510,829.22
Spatial standard deviation	6.00	1.46	3.51–9.23

Figure 5. Posterior mean of the spatial random effect. Posterior mean estimates of the spatial random effect from the Bayesian spatial model after adjustment for observed facility-level covariates. Red shades represent positive residual spatial effects and blue shades represent negative residual spatial effects, with white indicating values close to zero **(Figure 5)**.

Figure 5. Posterior mean of the spatial random effect

Figure 6. Posterior standard deviation of the spatial random effect. Posterior standard deviations of the spatial random effect from the Bayesian spatial model, representing the uncertainty associated with the estimated residual spatial effects. Lighter colours indicate lower posterior uncertainty and darker colours indicate greater posterior uncertainty **(Figure 6)**.

Figure 7. Posterior exceedance probability of a positive spatial random effect. Posterior probability that the spatial random effect exceeds zero, from the Bayesian spatial model after adjustment for observed facility-level covariates. Darker blue shades indicate stronger posterior evidence for positive residual spatial effects, whereas lighter shades indicate weaker evidence (Figure 7).

Discussion

Principal findings

This nationally representative study provides the first comprehensive assessment of emergency obstetric and newborn care readiness across Ethiopian health facilities with Bayesian hierarchical spatial modelling. Four principal findings emerged. First, emergency readiness demonstrated substantial regional and facility-level variation, with moderate inequality across health facilities. Second, provider availability and oxytocin availability remained independently associated with higher emergency readiness after accounting for regional heterogeneity and spatial dependence, whereas the proportion of trained providers showed no independent association. Third, medium clinics exhibited substantially lower readiness than the reference facility category, indicating important structural differences in emergency service capacity across facility levels. Finally, accounting for regional and spatial dependence identified residual geographically structured variation beyond measured facility characteristics.

National emergency readiness and inequality

The nationally weighted mean CERI was considerably lower than the corresponding unweighted estimate, indicating that emergency obstetric readiness may be overestimated when complex survey design is ignored. In addition, the moderate Gini coefficient and wide regional variation demonstrate that emergency readiness is unevenly distributed across Ethiopian health facilities. These findings suggest that improvements in national service coverage have not translated into equitable emergency preparedness throughout the health system.

Our findings are consistent with recent analyses of the 2021–2022 Ethiopia Service Provision Assessment, which reported that only about half of health facilities were able to provide functional

emergency obstetric and newborn care signal functions and that national Basic Emergency Obstetric and Newborn Care (BEmONC) coverage remained below WHO recommendations (3). Similarly, comparisons of readiness indices derived from SPA and WHO Service Availability and Readiness Assessment frameworks showed that conventional additive indicators may inadequately capture the multidimensional nature of emergency preparedness, supporting the use of more comprehensive composite measures such as the CERI (4). Earlier national assessments likewise documented substantial variation in the availability of emergency obstetric signal functions, essential medicines and referral capacity across Ethiopian facilities (7).

These findings indicate persistent differences in health-system capacity despite continued investments in maternal and newborn health services. National reviews of maternal and newborn health programmes have shown that improvements in service availability have not consistently been accompanied by comparable improvements in facility readiness or quality of care, particularly outside higher-level hospitals (8).

Provider availability and oxytocin availability

After accounting for spatial dependence and regional heterogeneity, provider availability remained independently associated with higher emergency readiness. This finding is consistent with evidence from Ethiopia showing that adequate health workforce capacity is a fundamental component of emergency obstetric and newborn care readiness because sufficient staffing supports continuous service availability, timely emergency response and implementation of essential obstetric interventions (8,9). National health facility assessments have similarly reported that shortages and unequal distribution of skilled health professionals remain important constraints to emergency obstetric service delivery, particularly in lower-level facilities and geographically underserved areas (1,3).

Greater provider availability may reflect stronger organisational capacity and sustained delivery of essential emergency obstetric services. Previous Ethiopian studies similarly reported higher readiness among facilities with greater workforce capacity (5,10). Together, these findings suggest that provider availability represents an important indicator of overall facility preparedness.

Oxytocin availability demonstrated the strongest positive association with emergency readiness in the final Bayesian model. Oxytocin is a WHO-recommended tracer medicine for assessing emergency obstetric care readiness (11–13). Previous Ethiopian studies have consistently reported that shortages of essential obstetric medicines, including oxytocin, remain a major limitation to emergency obstetric service delivery despite improvements in institutional delivery and facility expansion (3,7).

The strong association between oxytocin availability and CERI likely reflects broader differences in facility preparedness rather than medicine availability alone. Oxytocin availability likely reflects broader facility capacity to maintain essential medicines and service readiness, consistent with previous Ethiopian facility assessments (4,8).

Facility-level determinants

Emergency readiness varied substantially across facility types. Medium clinics demonstrated markedly lower readiness than the reference facility category after adjustment for measured facility characteristics and spatial variation, whereas no independent differences were observed for hospitals or health centres. This finding is consistent with Ethiopia's tiered health system, in which hospitals are expected to provide comprehensive emergency obstetric and newborn care, while medium clinics are not routinely equipped or mandated to deliver the full range of emergency obstetric functions (3,14). Earlier national assessments similarly documented lower availability of essential medicines, emergency equipment and obstetric signal functions in lower-level facilities than in hospitals (3,7).

Although government-managed facilities demonstrated higher unadjusted readiness than privately managed facilities, ownership was not independently associated with emergency readiness after accounting for facility characteristics and spatial dependence. This suggests that differences observed in descriptive analyses were largely explained by underlying variations in facility resources and geographical context rather than management authority itself. Similar findings have been reported in Ethiopian health facility assessments, where structural resources and service capacity explained much of the variation previously attributed to ownership categories (1,4).

The proportion of trained providers was not independently associated with emergency readiness after adjustment. The SPA indicator may not adequately capture the quality, competency or recency of training. Previous Ethiopian studies have similarly highlighted that structural readiness depends on the combined availability of trained personnel, medicines, equipment and infrastructure rather than any single component in isolation (5,8).

Bayesian spatial modelling and geographical implications

Incorporating spatial dependence substantially improved model performance compared with non-spatial models, indicating that emergency obstetric readiness is influenced by geographical processes beyond measured facility characteristics. Spatial modelling accounted for geographical dependence that was not explained by measured facility characteristics (15).

The significant spatial autocorrelation observed before model adjustment indicates that emergency readiness was geographically clustered rather than randomly distributed. Similar spatial clustering has been reported for maternal health service utilisation, emergency obstetric care accessibility and health facility readiness in Ethiopia, reflecting underlying geographical differences in health-service capacity, infrastructure and accessibility (2,3,5). Our findings extend this evidence by demonstrating that, although much of the geographical variation was explained by observed facility characteristics, important residual spatial heterogeneity persisted, suggesting that unmeasured contextual factors also contribute to differences in emergency readiness.

The estimated spatial range further indicates that residual geographical dependence extended beyond individual facilities and administrative boundaries. This finding suggests that emergency readiness is shaped by broader health-system environments, including regional service organisation, medicine distribution systems, workforce deployment and geographical accessibility, rather than by isolated facility characteristics alone. Similar conclusions have been reported in recent geospatial analyses of emergency obstetric services in Ethiopia, which showed that geographical accessibility and health-system organisation jointly influence equitable access to emergency care (5).

Limitations

Several limitations should be considered when interpreting these findings. First, the cross-sectional design of the Ethiopia Service Provision Assessment precludes causal inference. Accordingly, the reported associations should be interpreted as correlations rather than causal effects.

Second, the CERI measures structural emergency readiness based on facility resources available at the time of assessment and does not evaluate the quality of clinical care, provider competence, adherence to clinical guidelines or maternal and neonatal health outcomes. Consequently, higher readiness scores should not be interpreted as direct evidence of better clinical performance.

Third, the analysis was restricted to variables collected in the Service Provision Assessment. Important determinants of emergency readiness, including supply-chain performance, facility financing, referral efficiency, governance, transportation accessibility and local contextual factors, were not available and therefore could not be evaluated. Although the Bayesian spatial model accounted for unobserved geographical variation, residual confounding from unmeasured factors cannot be excluded.

Finally, the 2021–2022 Ethiopia Service Provision Assessment did not include facilities in the Tigray region because of the security situation during data collection. Therefore, the findings should be interpreted as nationally representative for the surveyed regions rather than the entire country.

Despite these limitations, the use of nationally representative data, survey-weighted estimation, multidimensional readiness measurement and Bayesian hierarchical spatial modelling provides nationally representative evidence on geographical variation and facility-level determinants of emergency obstetric readiness in Ethiopia.

Policy implications

This study demonstrates substantial geographical and facility-level variation in emergency obstetric and newborn care readiness across Ethiopian health facilities. These findings indicate that monitoring national average readiness alone may not adequately identify facilities and regions with comparatively lower emergency preparedness. Incorporating multidimensional readiness measures such as the Comprehensive Emergency Readiness Index into routine health-system monitoring could complement existing service availability indicators by identifying geographical disparities in structural readiness.

The independent associations of provider availability and oxytocin availability with emergency readiness indicate that these indicators may serve as practical measures for monitoring facility preparedness within routine health-system assessments. The lower readiness observed among medium clinics and the residual geographical variation identified after spatial adjustment further suggest that strengthening emergency readiness may require approaches that consider both facility characteristics and geographical context.

Collectively, these findings provide nationally representative evidence that may support implementation and monitoring of Ethiopia's maternal and newborn health strategies, Universal Health Coverage agenda and Sustainable Development Goal 3 by informing more equitable assessment and prioritisation of emergency obstetric and newborn care readiness across the health system.

Conclusion

Emergency obstetric and newborn care readiness remains unevenly distributed across Ethiopian health facilities, with substantial geographical and facility-level variation and moderate national inequality. After accounting for regional heterogeneity and spatial dependence, provider availability, oxytocin availability and medium clinic status were independently associated with emergency readiness. Bayesian hierarchical spatial modelling identified residual geographically structured variation after adjustment for measured facility characteristics.

These findings provide nationally representative evidence that complements existing assessments of service availability by identifying geographical inequalities and facility-level differences in structural emergency readiness. Integrating multidimensional readiness assessment with spatial analytical approaches may strengthen routine monitoring and support more equitable prioritisation of emergency obstetric and newborn care services within Ethiopia's health system.

Declarations

Ethics approval and consent to participate

The study uses publicly available SPA data obtained with authorization from the DHS Program. Ethical approval for the original survey was obtained by the Ethiopian Public Health Institute Institutional Review Board and the ICF Institutional Review Board, and the survey was conducted in accordance with the ethical principles outlined in the **Declaration of Helsinki**. Permission to access and use the SPA 2021-2022 data was formally obtained from the DHS Program following an approved data request. The dataset used for this analysis is fully anonymized and publicly available; therefore, no additional ethical approval or informed consent was required for the present study.

Consent for Publication

Not Applicable

Data Availability

The data underlying the results presented in the study are publicly available from the Demographic and Health Surveys (DHS) Program upon request at https://dhsprogram.com and materials are available upon request.

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Competing Interest

The authors have declared that no competing interests exist.

Clinical trial number

Not applicable

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Figures

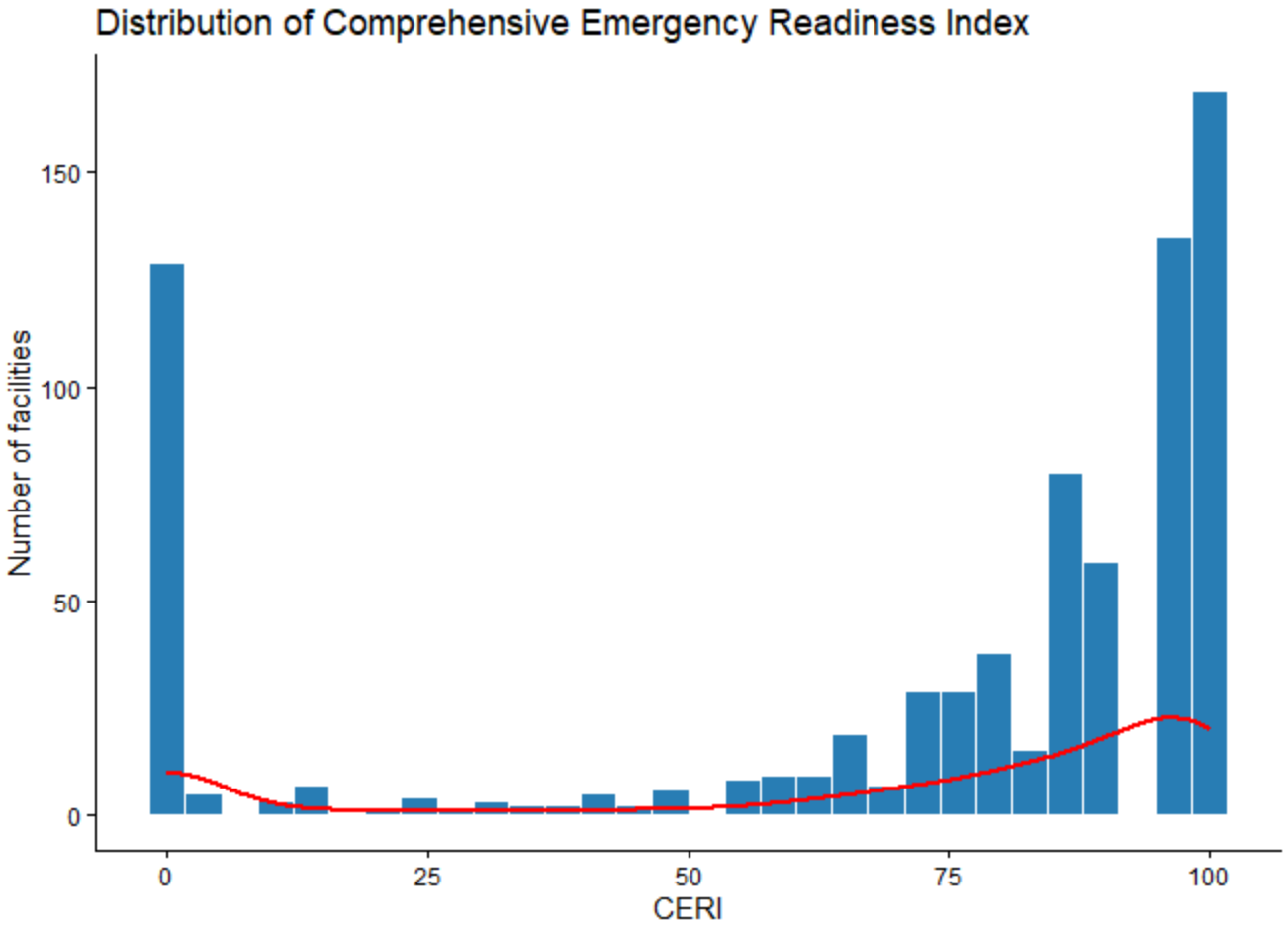


Figure 1

Distribution of the Comprehensive Emergency Readiness Index among health facilities in Ethiopia.

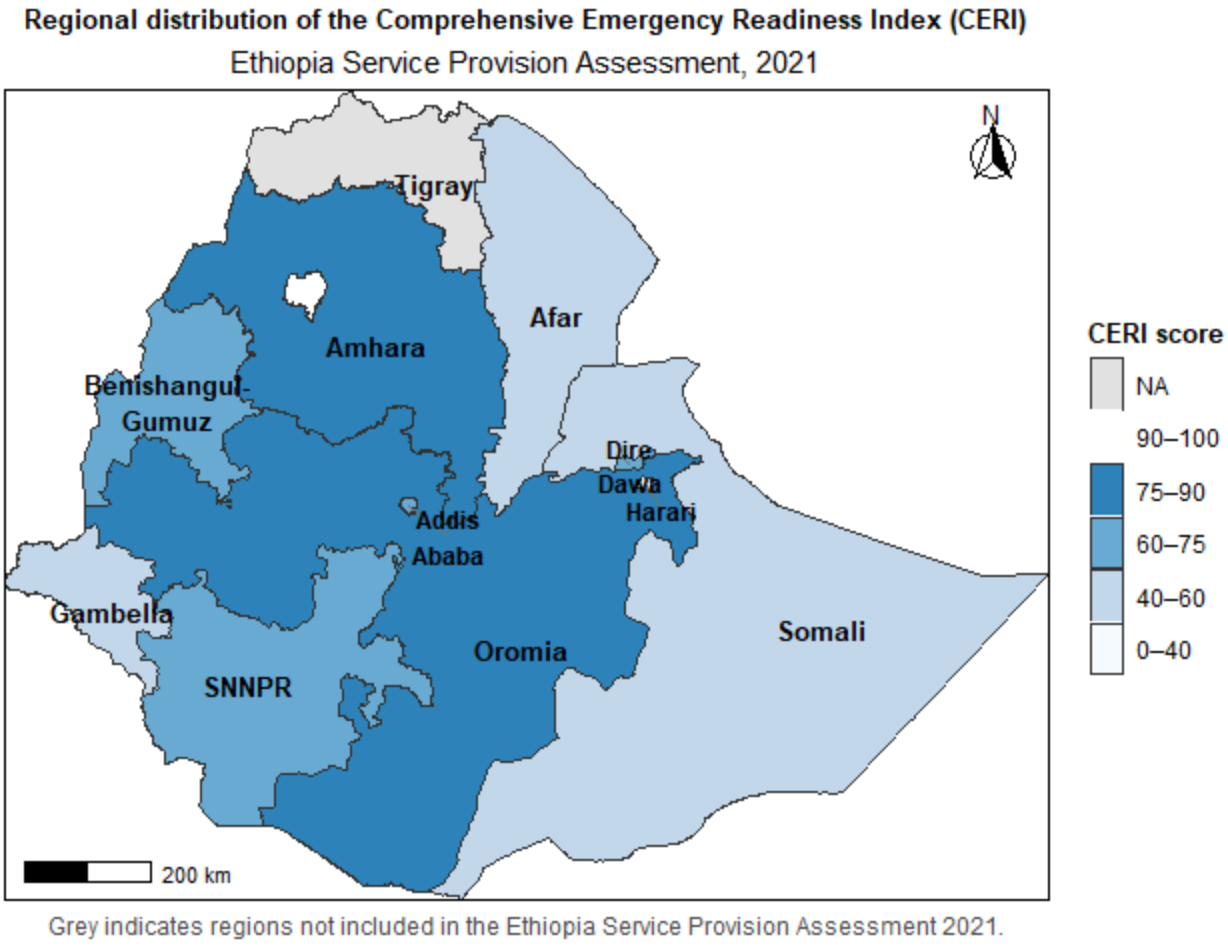


Figure 2

Regional distribution of the survey-weighted Comprehensive Emergency Readiness Index across Ethiopia.

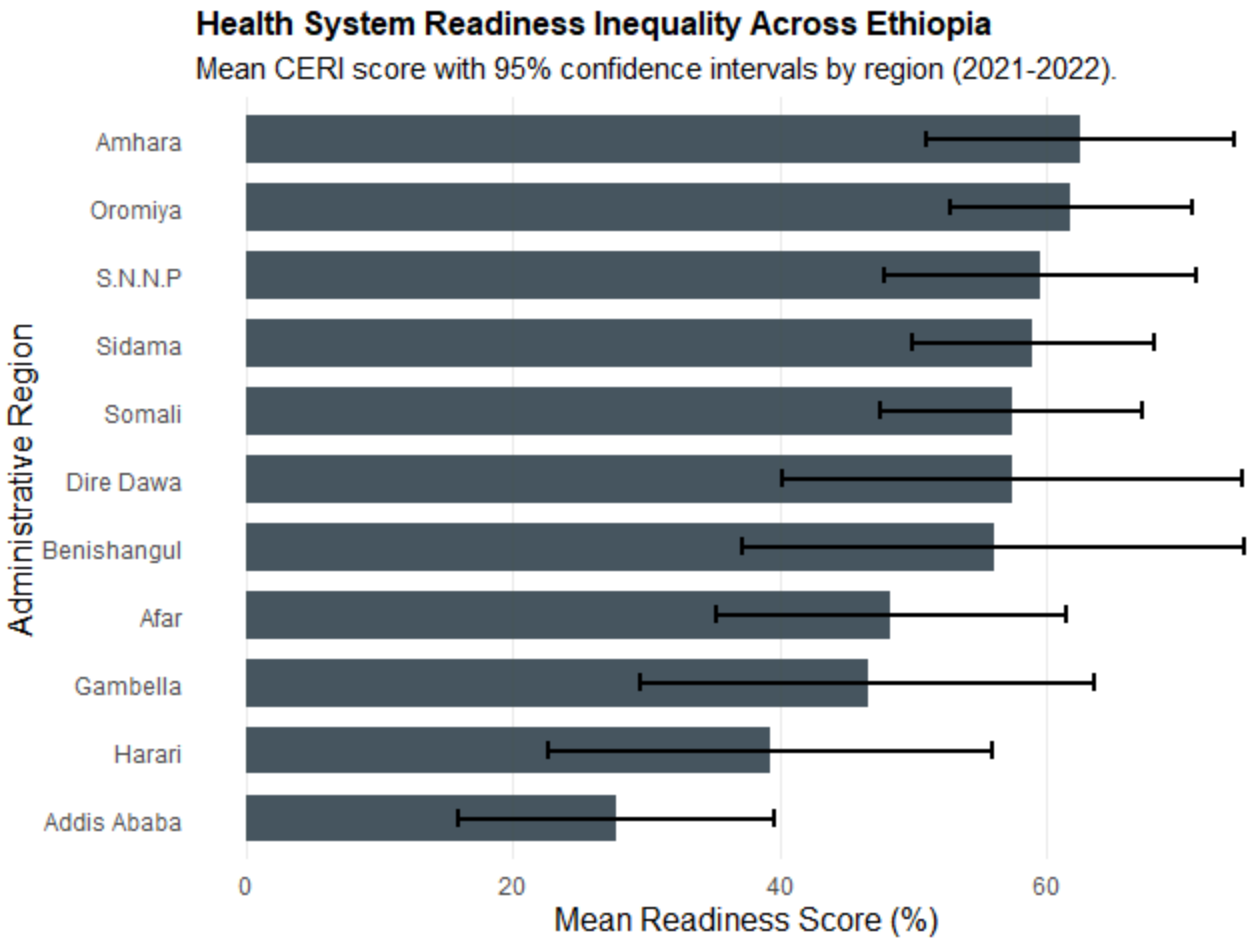


Figure 3

Survey-weighted regional mean Comprehensive Emergency Readiness Index with 95% confidence intervals.

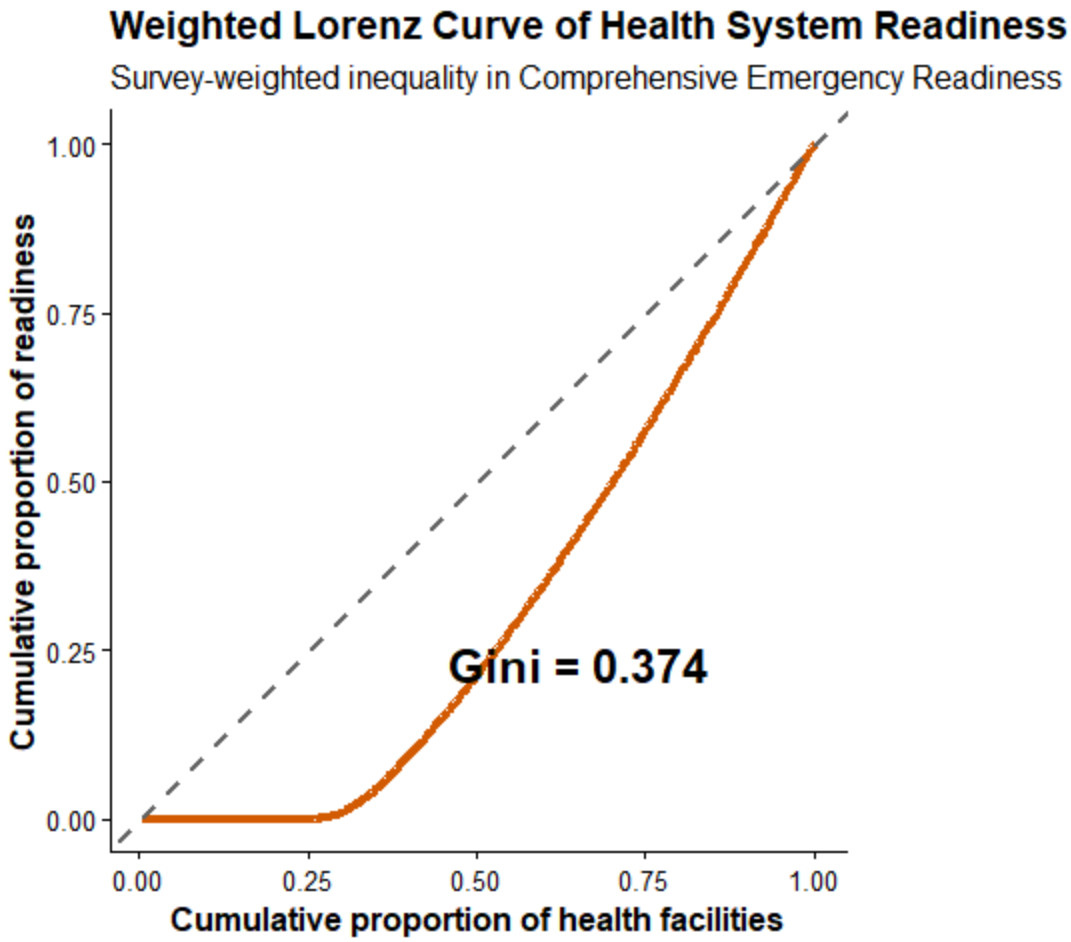


Figure 4

Weighted Lorenz curve showing inequality in the distribution of the Comprehensive Emergency Readiness Index among Ethiopian health facilities.

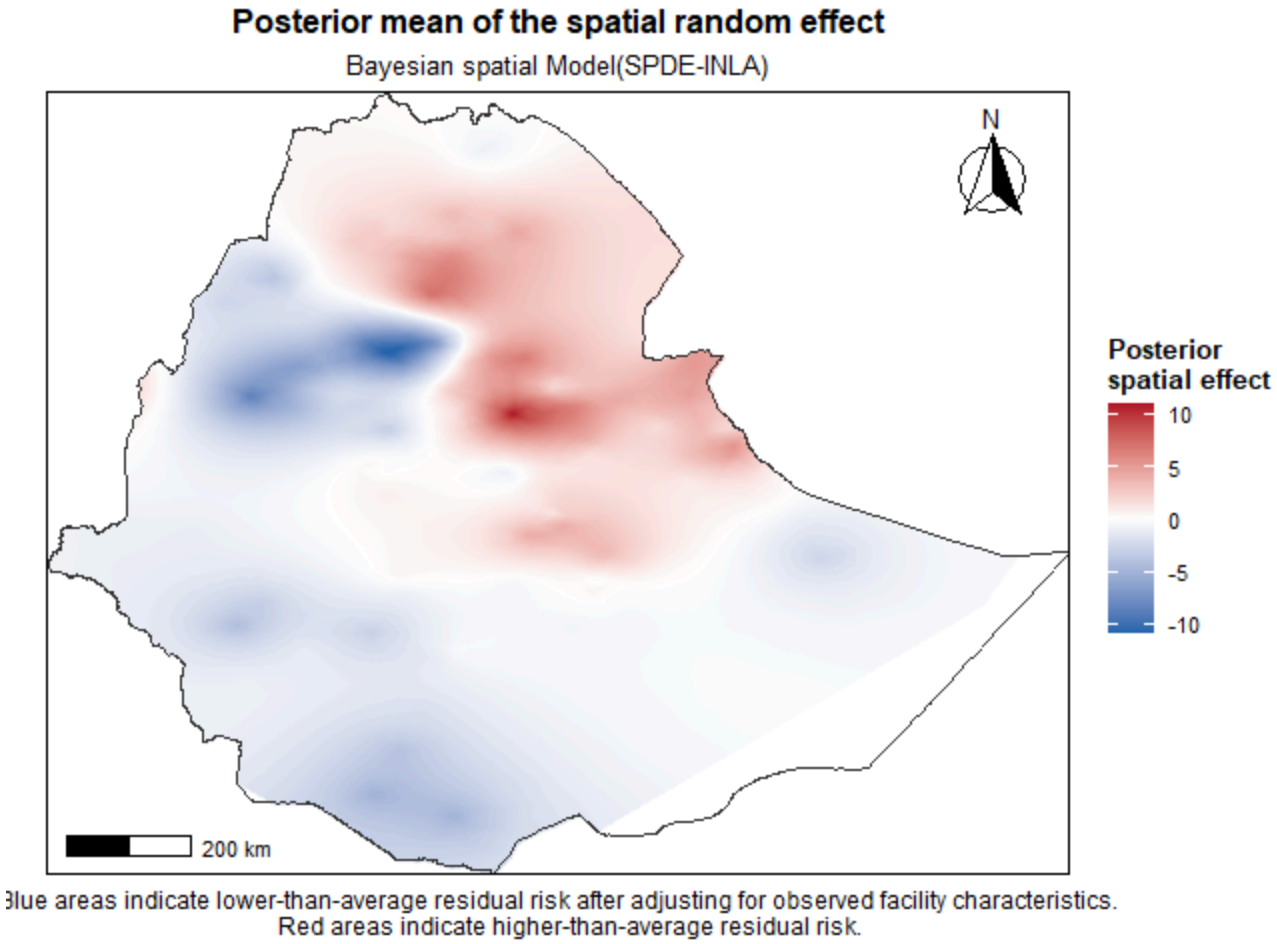


Figure 5

Posterior mean of the spatial random effect. Posterior mean estimates of the spatial random effect from the Bayesian spatial model after adjustment for observed facility-level covariates. Red shades represent positive residual spatial effects and blue shades represent negative residual spatial effects, with white indicating values close to zero **(Figure 5)**.

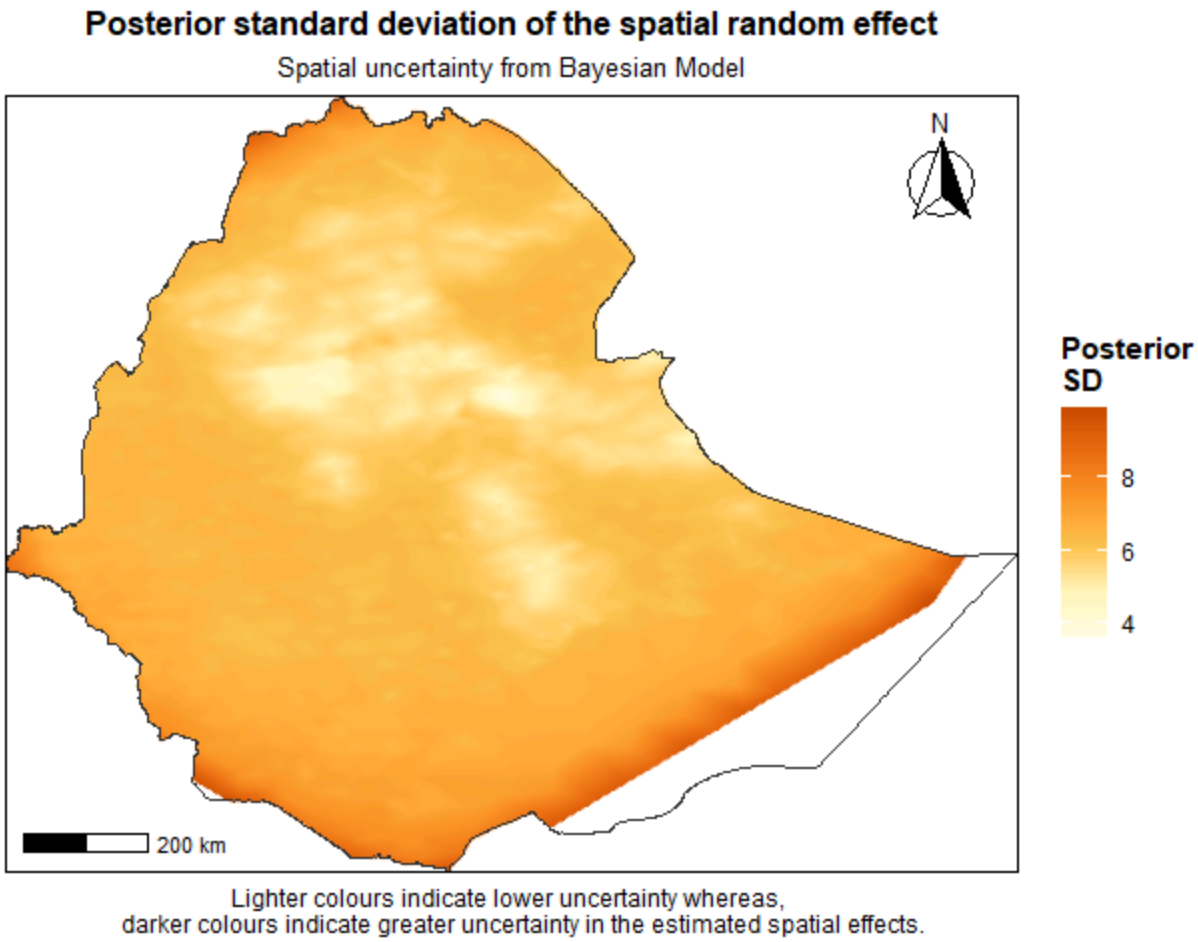


Figure 6

Posterior standard deviation of the spatial random effect. Posterior standard deviations of the spatial random effect from the Bayesian spatial model, representing the uncertainty associated with the estimated residual spatial effects. Lighter colours indicate lower posterior uncertainty and darker colours indicate greater posterior uncertainty **(Figure 6)**.

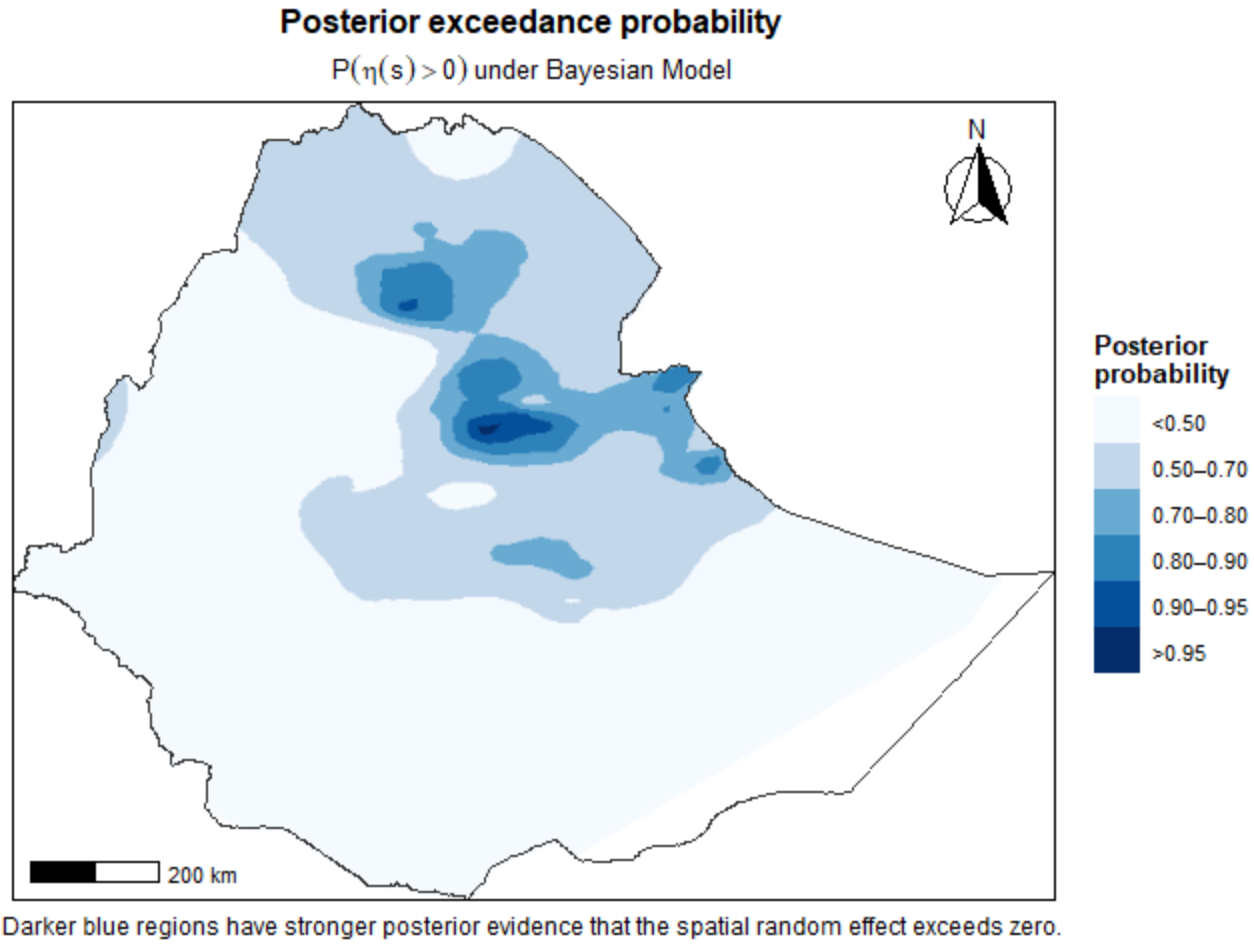


Figure 7

Posterior exceedance probability of a positive spatial random effect. Posterior probability that the spatial random effect exceeds zero, from the Bayesian spatial model after adjustment for observed facility-level covariates. Darker blue shades indicate stronger posterior evidence for positive residual spatial effects, whereas lighter shades indicate weaker evidence **(Figure 7).**