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Geospatial assessment of primary healthcare centres in Jeddah, Saudi Arabia

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Abstract

Rapid urban growth has increased concerns about spatial equity in access to Primary Healthcare Facilities (PHCs), particularly in contexts where proximity-based assessments may overestimate effective access by overlooking population demand and service capacity. This study evaluates district-level accessibility and equity of PHCs in Jeddah, Saudi Arabia using a capacity-sensitive Modified Two-Step Floating Catchment Area (M2SFCA) framework incorporating population weighting, distance decay and bed capacity. Network-based service area analysis was used to define catchment thresholds, while origin–destination cost matrices supported accessibility indexing. Spatial patterns were examined using Global Moran's *I*, and distributional equity was assessed through coefficient of variation, percentile ratio, accessibility shares, Gini coefficient and Lorenz curves. A planning-oriented location–allocation model evaluated a scenario-based PHC expansion. Results show that although approximately 69% of the urban area lies within nominal PHC catchments, baseline accessibility exhibits noticeable spatial inequities, with near-zero access in several peripheral districts and significant spatial clustering (Moran's $I = 0.398$). The proposed scenario introducing four PHCs with varied capacity produced systematic improvements in underserved areas. The percentage ratio declined sharply from 81.34 to 9.13, demonstrating substantial disparities between the highest and lowest-access districts. This increased the accessibility share of the bottom 40% of the population, and lowered overall inequality from 0.191 to 0.172 while slightly weakening spatial clustering. The findings demonstrate that capacity-aware accessibility modelling integrated with planning scenarios provides policy-relevant insights for improving spatial equity in PHC provision and is transferable to other rapidly urbanizing urban contexts.

Key words: healthcare accessibility; spatial equity and inequality; Primary Healthcare Centres (PHCs); Two-Step Floating Catchment Area (2SFCA); spatial autocorrelation, Saudi Arabia.

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Introduction

Primary Healthcare Facilities (PHCs) constitute the backbone of urban health systems and play a critical role in promoting population well-being and productivity, particularly for local communities (Zhang, 2022). In rapidly urbanizing cities, however, population growth and spatial expansion often outpace healthcare provision, creating persistent spatial inequities in access to primary care services (Du *et al.*, 2024). These imbalances are frequently driven not only by the location of facilities but also by unequal distribution of service capacity, especially bed availability which remains a key challenge for public health authorities (Chen *et al.*, 2024). Methods based on Geographic Information System (GIS) have been widely applied to evaluate healthcare accessibility, network-based Service Area (SA) analysis, and Floating Catchment Area (FCA) models (Pérez-Fernández & Michel, 2025). While SA analysis is useful for identifying nominal geographic coverage, it does not account for population demand, facility competition or service capacity, and may therefore substantially overestimate realized access. FCA-based approaches, particularly the two-step Floating Catchment Area (2SFCA) method, address some of these limitations by integrating supply–demand relationships within defined catchments (Liu *et al.*, 2020). Enhancement of the 2SFCA framework have further incorporated distance decay, hierarchical facility structures and multimodal travel to better reflect healthcare utilization patterns in large cities (Tao *et al.*, 2020).

In the Saudi Arabian context, accessibility assessments have predominantly relied mostly on travel distance or time dependent thresholds, often treating PHCs as homogeneous service points and overlooking variation in service capacity (Khashoggi & Murad, 2021). Such simplifications are problematic in rapidly growing cities like Jeddah, where facilities may exist within acceptable travel times but operate with limited resources, leading to constrained effective access. This is particularly relevant given international benchmarks such as the World Health Organization's recommended 2.9 beds per 1,000 population, which highlights the importance of capacity-sensitive evaluation (Kattan & Alsareef, 2022). Moreover, most existing studies remain descriptive and static, offering limited guidance on how identified inequities could be addressed through targeted planning interventions (Zhang *et al.*, 2021; Robbennolt & Witmer, 2023; Alhubashi *et al.*, 2024).

Recent methodological advances emphasize the value of modified 2SFCA (M2SFCA) models, which incorporate distance-decay effects and population weighting to provide a more realistic

representation of accessibility under capacity constraints (Delamater, 2013). Beyond measurement, several studies highlight the importance of linking accessibility modelling with planning-oriented tools such as Location–Allocation (LA) analysis to support actionable and equity-focused decision-making (Abdelkarim, 2019; AlFanatseh & Sababhi, 2022). From an equity perspective, combining horizontal equity meaning equal access for equal need and vertical equity that accounts for variations in population size and service demand remains essential for meaningful evaluation of PHC systems (Kuwawenaruwa *et al.,* 2017).

This study advances existing research in the urban context of Saudi Arabia by linking capacity-aware accessibility measurement with equity diagnostics and planning-oriented optimization to find a transferable, evidence-based approach for urban health systems seeking to reduce spatial inequities through targeted, capacity-sensitive primary healthcare planning.

Materials and Methods

Jeddah, one of Saudi Arabia's fastest-growing metropolitan areas, presents a critical case for examining the challenges discussed above. The city exhibits noticeable spatial heterogeneity in population distribution, with high-density districts concentrated along the urban core and expanding peripheral areas in recent years. Within the Kingdom's multi-sector healthcare system, comprising Ministry of Health (MoH) PHCs, other governmental providers and private facilities, the PHCs serve as the primary point of contact for most residents and are central to MOH equity-driven health policies (Alabbasi *et al.*, 2023). However, empirical evidence on how PHC service capacity aligns spatially with population demand across Jeddah's 115 administrative districts remains limited. Figure 1a illustrates the locations of PHCs with bed capacity and 1b exhibits population density map of Jeddah. While GIS-based assessments of primary healthcare accessibility are well established, this study advances existing work in several important ways especially in the Saudi context. First, unlike prior PHC accessibility studies in Saudi Arabia that rely primarily on proximity or travel-time thresholds, this research explicitly incorporates PHC service capacity, using bed availability as a key indicator for healthcare supply within a M2SFCA framework. Second, the study moves beyond descriptive accessibility mapping by integrating capacity-aware accessibility outputs with LA modelling, enabling the evaluation of policy-driven expansion scenarios rather than static assessment alone. Third, spatial equity is examined using a comprehensive set of distributional equity metrics including Coefficient of Variance (CV), percentile ratio (P_{90}/P_{10}), bottom 40% accessibility share (B_{40}), top 20% accessibility share (T_{20}) and Gini coefficient are used to assess inequality that are rarely addressed in the Saudi PHC literature. Finally, the proposed scenarios are explicitly aligned with Saudi MoH planning objectives, ensuring that methodological outputs are directly relevant for evidence-based primary healthcare infrastructure planning.

Data collection and sources

This study utilized secondary spatial and attribute data obtained from Ministry of Municipal, Rural Affairs and Housing (MOMRAH). Spatial datasets included administrative boundaries of 115 districts in Jeddah, locations of PHCs, and a detailed street network. Attribute data consisted of district-level population and PHC bed capacity information. Similar data structures have been widely adopted in GIS-based healthcare accessibility studies (Khashoggi & Murad, 2021; Pérez-Fernández & Michel, 2025). District boundaries were represented as polygon features, while PHCs were mapped as point features with associated attributes describing facility type and number of available beds. District population data were joined to administrative boundaries and later transferred to centroid points generated using the "Feature to Point" ArcGIS tool to represent population demand locations. All spatial analyses were conducted in ArcGIS Pro (version 3.0.1). To ensure spatial consistency, all datasets were projected to WGS 1984 UTM Zone 37N, which is appropriate for western Saudi Arabia (GASGI, 2022). Table 1 shows the lists of data collected for this research.

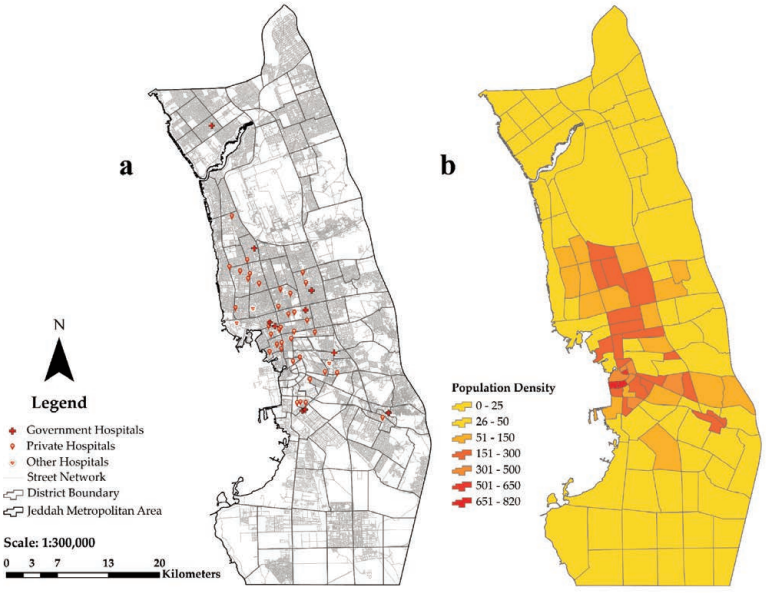

Figure 1. a) Existing PHCs including street network and **b**) Population density map of Jeddah.

Network dataset preparation

A network dataset was developed from the street centre line data using the Network Analyst toolset in ArcGIS Pro. Each road segment was attributed with length and travel speed to allow network-based distance and travel time calculations. Network-based measures were preferred over Euclidean distance, as travel time more accurately represents real-world access to healthcare services (Tseng *et al.*, 2013; Khashoggi & Murad, 2021). Based on local urban travel conditions and prior healthcare accessibility studies, a 20 km travel distance, corresponding approximately to 30 minutes of driving time in Jeddah, was selected as the catchment threshold. This threshold is consistent with empirical studies that identify travel times beyond 30 minutes as a barrier to effective primary healthcare access (Nicholas *et al.*, 2014; Alfred *et al.*, 2015). The network dataset formed the basis for SA analysis, origin-destination (O-D) cost matrix generation, and LA modelling.

Service area assessment and origin–destination cost matrix

SA analysis was conducted to delineate the spatial coverage of existing PHCs along the street network. PHCs were used as facilities, and a 20 km impedance cut-off was applied to identify areas reachable within the defined travel threshold. This step provided an initial overview of geographic service coverage and supported identification of potentially underserved districts, consistent with prior urban health planning studies (Amaguaya & Hernández, 2020; Wagistina *et al.*, 2022). To support accessibility modelling, O–D cost matrix was generated using district centroid points as origins and PHCs as destinations. The O–D matrix calculated network-based distances between each district and all PHCs within the catchment. District population and PHC bed capacity attributes were joined to the O–D table, forming the analytical foundation for subsequent accessibility calculations (Khashoggi & Murad, 2021).

Accessibility modelling using the M2SFCA Method

Compared to the classical 2SFCA, M2SFCA incorporates distance decay and population weighting, thereby reducing the assumption of uniform accessibility within catchment areas and better reflecting realistic healthcare utilization patterns (Liu *et al.*, 2020; Tao *et al.*, 2020). First step of accessibility modelling is to identify capacity to demand ratio. For each PHC j, a capacity-to-demand ratio R_j was calculated as:

$$R_j = \frac{S_j}{\sum_{i:d_{ij}\le d_0} P_i . W(dij)} \qquad \text{Eq. 1}$$

where, S_j is the number of available beds at PHC j, ; P_i the population of district i, ; d_{ij} the network distance between district i and PHC j, ; d_0 the 20 km catchment threshold; and $W(d_{ij})$ is a distance-decay weight that reduces the influence of more distant populations. Second step is to compute the accessibility index for all PHCs within the catchment area based on the 20 km catchment threshold. For each district , the accessibility score was calculated by summing the weighted capacity ratios of all PHCs within the catchment:

$$A_i = \sum_{j:d_{ij}\le d_0} R_j . W(dij) \qquad \text{Eq. 2}$$

Accessibility values were scaled to beds per 1,000 population to facilitate interpretation and comparison with international benchmarks.

Spatial autocorrelation analysis using Global Moran's *I*

To examine the spatial structure of accessibility outcomes, this statistic was applied to district-level Aj_{1000} values. It evaluated whether spatial patterns are clustered, dispersed or random at the city-wide scale (Tsai *et al.*, 2009; Cheng *et al.*, 2024).

$$I = \frac{N}{W} \cdot \frac{\sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} w_{ij}(X_i - \bar{X})(X_j - \bar{X})}{\sum_{i=1}^{N}(X_i - \bar{X})^2} \qquad \text{Eq. 3}$$

where I measures spatial autocorrelation; N the total number of districts; W the sum of weights between districts; w_{ij} the spatial weight between districts i and j; X_i the value of A_i beds per 1000 population for district i; $\bar{X}$ the mean value of A_i beds per 1000 population; and X_j the value of A_i beds per 1000 population for district j.

The analysis was conducted in ArcGIS Pro using district polygons with spatial relationships defined by contiguity-based weights and row standardization. The resulting Moran's I, z-score and p-value were used to assess statistical significance of spatial clustering under both baseline and proposed scenarios.

Location-allocation modelling for PHC expansion

To evaluate planning-oriented improvement scenarios, LA modelling was employed using the Network Analyst extension. Underserved districts identified from baseline accessibility results served as demand points. Proposed locations for new PHCs were generated based on network accessibility and spatial gaps in service coverage. A maximum coverage model was adopted to identify optimal locations for four new PHCs, each assigned to a varied bed capacity. These numbers were treated as a policy-driven scenario rather than a full optimization solution, reflecting realistic incremental expansion strategies commonly used in urban healthcare planning (Abdelkarim, 2019; Karim & Awawdeh, 2020). The same 20 km impedance threshold was maintained to ensure consistency across analyses. Among the seven types of LA models, max-

Table 1. Collected data and attributes.

Dataset	Type	Description	Format
District population	Attribute	Population living in each district	Polygon and Point
District boundary	Spatial	Boundary of 115 districts	Polygon
Healthcare facilities	Spatial Attribute	Location of PHCs Name, number of available beds, type of PHCs (public, private and others)	Point
Street network	Spatial	Centreline of the roads	Line

imum coverage was used for this study stated as:

$$Maximize\ Coverage = max\left(\sum_{j \in S} P_j\right) \quad \text{Eq. 4}$$

where P_j represents the population of district j within threshold limit; and S the set of PHCs with proposed locations. After facility allocation, the full accessibility modelling workflow following M2SFCA computation, and spatial autocorrelation analysis was repeated to evaluate changes both in accessibility and spatial patterns.

Equity metrics assessment

To quantify spatial equity in healthcare accessibility, several distributional indicators were computed. In addition to the CV and P_{90}/P_{10}, concentration-based equity measures were employed. The bottom 40% accessibility share (B_{40}) captures the proportion of total accessibility allocated to the least-served 40% of the population, while the top 20% accessibility share (T_{20}) reflects the concentration of accessibility among the most advantaged 20%. Accessibility was weighted by population to ensure that equity was evaluated in relation to both service capacity and population demand. Overall inequality was further assessed using the Gini coefficient, derived from the Lorenz curve, which compares the cumulative share of population with the cumulative share of accessibility. Accessibility values were weighted by population to ensure that equity assessment reflected both service capacity and population demand. CV measures the relative dispersion of accessibility values across districts and provides a scale-independent indicator of inequality. It is defined as:

$$CV = \frac{\sigma}{\mu} \quad \text{Eq. 5}$$

where, σ is the Standard Deviation (SD) of the district-level accessibility values; and is the mean accessibility value across all districts. Higher CV values indicate greater inequality in spatial accessibility, while lower values suggest a more even distribution of healthcare resources.

P_{90}/P_{10} ratio evaluates inequality between districts at the upper and

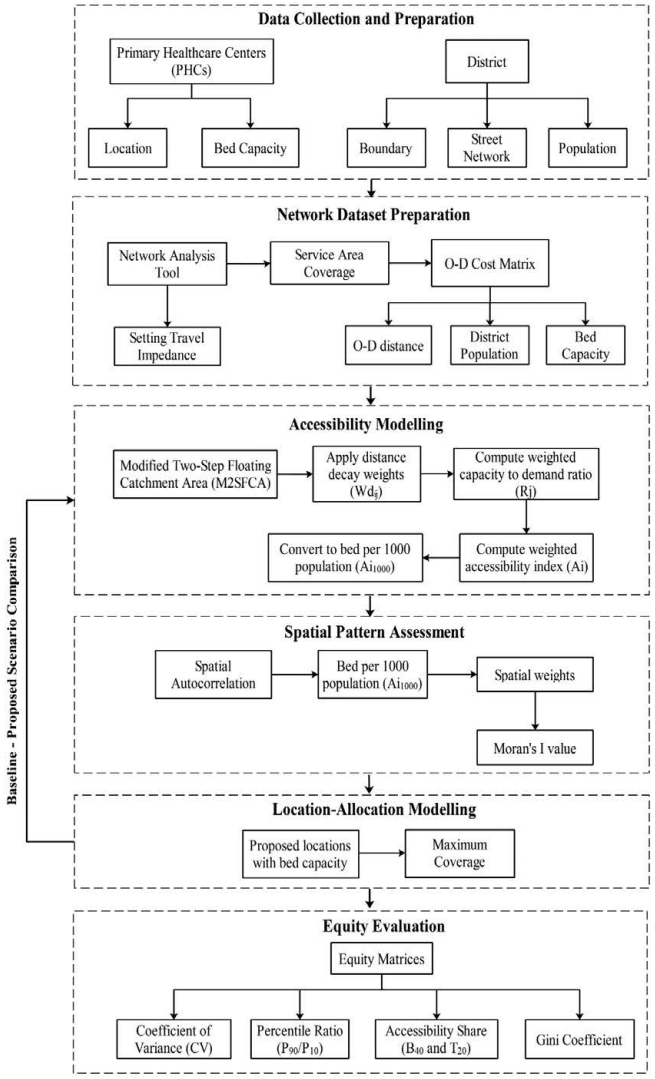

Figure 2. Research methodology.

lower ends of the accessibility distribution. It is calculated as:

$$\frac{P_{90}}{P_{10}} = \frac{A_{90}}{A_{10}} \quad \text{Eq. 6}$$

where, A_{90} represents the 90th percentile of accessibility values, and A_{10} the 10th percentile. A higher ratio indicates stronger division between well-served and poorly served districts, whereas a lower ratio reflects reduced inequality. To incorporate population distribution into equity assessment, this study computed population-weighted accessibility concentration indicators, denoted as B_{40} and T_{20} and calculated as:

$$B_{40} = \frac{\sum_{i \in bottom\ 40\%\ pop} A_i \cdot P_i}{\sum_{i=1}^{N} A_i \cdot P_i} \quad \text{and} \quad T_{20} = \frac{\sum_{i \in top\ 20\%\ pop} A_i \cdot P_i}{\sum_{i=1}^{N} A_i \cdot P_i} \quad \text{Eq. 7}$$

Figure 2 presents the methodological framework used to compare baseline and improvement scenarios for PHC accessibility. The framework evaluates the effects of targeted interventions, including the addition of four new PHCs with varied capacity from 30 to 500 beds each, on accessibility, spatial patterns, and equity outcomes. This approach enables a consistent assessment of how capacity expansion influences primary healthcare equity in Jeddah.

Results

SA analysis was conducted to provide an initial overview of the geographic reach of existing PHCs in Jeddah using a network-based approach. A 20 km travel-distance threshold, corresponding approximately to 30 minutes of driving time under urban traffic conditions, was applied to define areas potentially reachable from PHCs. Figure 3 illustrates the SA coverage under varying travel distance and time, whereas Table 2 summarizes the coverage achieved at incremental distance bands and their corresponding travel times under different assumed speeds. The results indicate that PHCs collectively cover a substantial proportion of the urban area within shorter travel distances, with coverage gradually increasing up to the 20 km threshold. Overall, approximately 69% of the study area falls within the defined service range, while the remaining 31% lies beyond this threshold or corresponds to sparse-

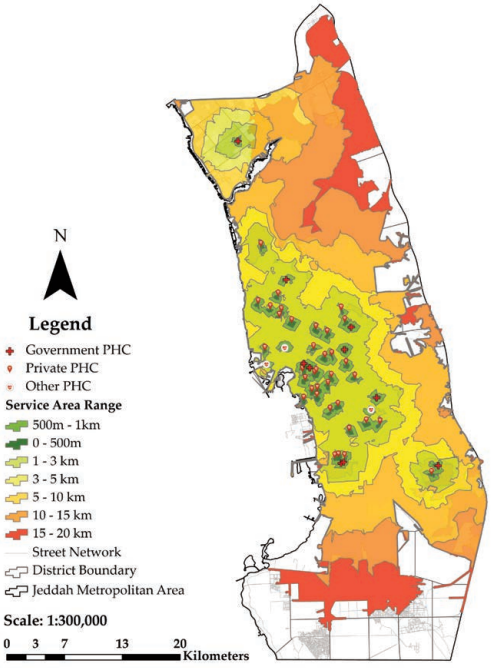

Figure 3. Service area coverage map of PHCs based on incremental distance and time.

Table 2. Service area coverage of PHCs based on travel distance and time.

Service area range	Drive Time (min) @60 km/hr.	Drive Time (min) @40 km/hr.	Drive Time (min) @30 km/hr.	Coverage (Area) Sq. km	Percentage of Area Coverage
0-500 m	0.5	0.8	1	12.82	1%
500 m - 1 km	1	1.5	2	45.25	4%
1 km - 3km	3	4.5	6	245.95	20%
3 km - 5 km	5	7.5	10	355.74	29%
5 km - 10 km	10	15	20	583.23	47%
10 km - 15 km	15	22.5	30	718.09	58%
15 km - 20km	20	30	40	852.56	69%
Underserved area	-	-	-	391.66	31%

ly developed or peripheral zones. It is important to emphasize that SA analysis reflects potential geographic coverage only and does not account for population demand or differences in PHC service capacity. As such, areas within the service boundary may still experience limited access in practice. Therefore, SA results are interpreted as an exploratory step used to define catchment thresholds and support subsequent analyses. Accessibility to primary healthcare services was quantified at the district level using the capacity-sensitive M2SFCA method, expressed as accessibility indices per 1,000 population following equation 1 and 2. Baseline accessibility results reveal substantial spatial heterogeneity, with several districts exhibiting extremely low or near-zero accessibility despite falling within nominal service area boundaries. Peripheral and rapidly developing districts such as Al Karamah, Al Rahmah, Al Barakah, Al Masarah, Al Moulysaa, and Al Qouzeen exhibit negligible baseline accessibility, highlighting the limitations of proximity-based coverage alone. To address these gaps, a scenario-based LA model was implemented, introducing four additional PHCs strategically distributed across the northern, central, southern, and lower-mid regions of the city (Figure 4b). Bed capacities varied from 30, 200, 350, and 500 beds to reflect realistic service hierarchies and operational constraints. To address persistent access gaps and larger catchment areas in the southern region, the proposed southern PHC was assigned a higher service capacity (500 beds), enabling the system to accommodate both current demand and anticipated future population growth while improving spatial equity across districts. The proposed configuration resulted in systematic improvements in accessibility across underserved districts, particularly those previously recording zero or minimal access. For example, accessibility in Al Karamah, Al Rahmah, Al Masarah, and Al Fadeyllah increased from near-zero baseline values to moderate or high levels under the proposed scenario. While accessibility gains were observed citywide, improvements were not uniform, reflecting the combined influence of population density, distance decay, and facility capacity within the M2SFCA framework. Established high-access districts such as Obhur Al Shamalyyah, Al Amwaj, and Al Sheraa retained high accessibility levels under both scenarios, whereas intermediate districts experienced moderate but meaningful gains. This pattern indicates that the proposed intervention improves access equity without disproportionately concentrating services in already well-served areas. Figure 4 illustrates the baseline and proposed scenario after implementation of LA model with proposed bed capacities. Distributional changes are further illustrated using boxplots of log-transformed accessibility values in Figure 5. The values demonstrated rightward shift in the median and a reduction in lower-tail compression under the proposed scenario. These results confirm that accessibility improvements are driven primarily by uplift in low-access districts rather than marginal gains in already high-access areas. Global Moran's *I* statistics indicate significant positive spatial autocorrelation of district-level accessibility under both scenarios (Table 3). In the baseline condition, accessibility exhibits strong spatial clustering reflecting pronounced concentration of higher access in specific urban cores and coastal districts alongside extensive low-access clusters in peripheral areas. Following equation 3 in ArcGIS pro, results show that Moran's I decreases to 0.374 with z score of 11.87 indicating a modest but meaningful reduction in spatial clustering. While accessibility remains significantly clustered, the lower Moran's *I* value suggests that improvements are more spatially distributed under the proposed scenario, particularly through uplift in previously underserved districts. The persistence of positive spatial autocorrelation highlights the influence of underlying population distribution and urban structure, while the observed reduction confirms that the proposed capacity-

Table 3. Spatial autocorrelation under baseline and proposed scenarios.

Parameters	Baseline	Proposed
Moran's I	0.398	0.374
Variance	0.001045	0.001042
z- score	12.59	11.87
p-value	0	0

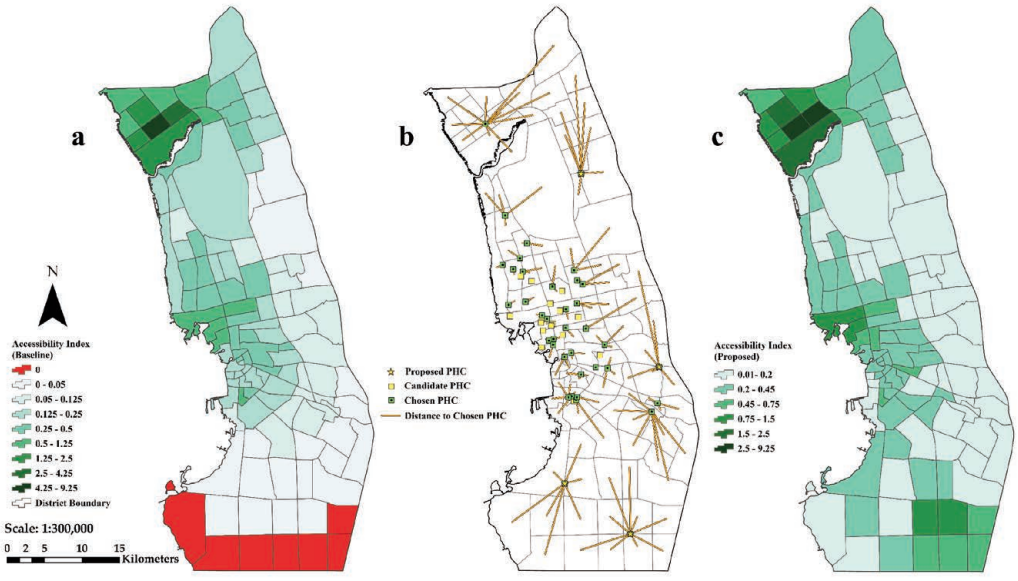

Figure 4. District-level PHC accessibility under baseline and proposed scenarios.

sensitive LA strategy contributes to improved spatial equity without destabilizing established high-access areas following equation 4. Distributional equity in district-level accessibility was evaluated using complementary inequality and polarization metrics, including the CV, the P_{90}/P_{10}, ratio, bottom 40% (B_{40}) and top 20% (T_{20}) accessibility shares, and the Gini coefficient (Table 4). Lorenz curves for both baseline and proposed scenarios are shown in Figure 6. Collectively, these measures provide a robust assessment of overall dispersion, extreme inequality, and tail-specific accessibility concentration. Following equation 5, CV increased from 2.60 under baseline conditions to 5.13 in the proposed scenario, indicating greater relative dispersion in accessibility values. This increase reflects the appearance of higher-access districts following the proposed PHCs rather than declining in access among low-access districts and therefore should not be interpreted as reduced equity in inaccessibility. In contrast, following equation 6, P_{90}/P_{10} ratio declined sharply from 81.34 to 9.13, demonstrating a substantial compression of extreme disparities between the highest and lowest-access districts. Tail-sensitive equity indicators further confirm this pattern following equation 7. Under baseline conditions, the bottom 40% of the population (B_{40}) accounted for approximately 16.5% of total accessibility, increasing to 19.2% under the proposed scenario. Conversely, the top 20% of the population (T_{20}) accounted for approximately 43.5% of total accessibility at baseline, which decreased modestly to 41.4% following the proposed intervention. These shifts indicate that accessibility gains are primarily driven by uplifts among previously low-access districts, accompanied by a moderate reduction in upper-tail concentration. This pattern is consistent with an equity-improving intervention that enhances access without penalizing already well-served areas. The decline in the Gini coefficient from 0.191 to 0.172 further confirms an overall reduction in accessibility inequality.

Discussion

This study demonstrates that nominal geographic coverage of PHCs in Jeddah substantially overstates effective access when population demand and facility capacity are not considered. While SA analysis suggests that a large portion of the city lies within acceptable travel-time thresholds, capacity-sensitive accessibility modelling reveals marked spatial inequities, particularly in southern and eastern districts. This finding confirms that SA analysis is useful mainly for defining catchment thresholds but is insufficient for evaluating realized access or supporting equitable healthcare planning. Similar limitations of proximity-based approaches have been demonstrated in earlier studies of Jeddah's healthcare system (Khashoggi & Murad, 2021). By incorporating bed capacity, distance decay, and population effects through the M2SFCA method, this study provides a more realistic assessment of PHC accessibility aligned with recent advances in healthcare accessibility modelling (Tao *et al.*, 2019; Sun *et al.*, 2024). Baseline results show strong concentration of access in central districts and persistent low-access conditions in peripheral areas, consistent with previous findings in Saudi urban contexts (Khashoggi & Murad, 2021). Importantly, integrating accessibility outputs with LA model enabled direct transformation of accessibility gaps into targeted planning actions, responding to calls for more decision-oriented assessment (Abdelkarim, 2019).

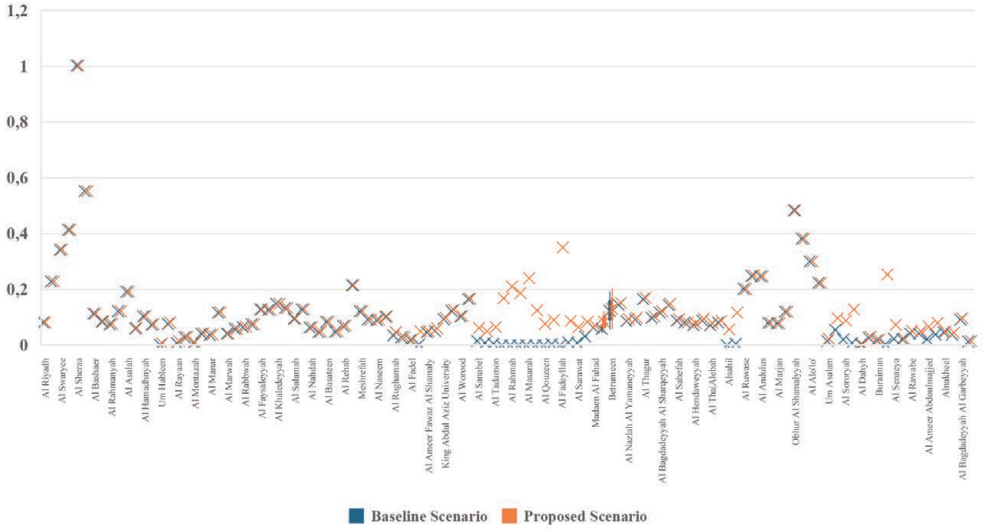

Figure 5. District-level comparison of primary healthcare accessibility under baseline and proposed scenarios using log-transformed accessibility indices.

Table 4. Equity and inequality metrics for district-level accessibility under baseline and proposed scenarios.

Metrics	Baseline	Proposed	Interpretation
Coefficient of Variance (CV)	2.6	5.13	Relative dispersion increases due to strong improvement in previously low-access districts
P_{90}/P_{10}	81.34	9.13	Extreme upper–lower accessibility inequality reduced substantially
B_{40}	0.165	0.192	Extreme upper–lower accessibility inequality reduced substantially
T_{20}	0.435	0.414	Accessibility concentration among the top 20% decreases
Gini Coefficient	0.191	0.172	Overall accessibility inequality declines

The proposed scenario reflects key Saudi MoH policy objectives focused on improving equity, reducing regional disparities, and planning for future population growth. Assigning higher capacity to the proposed southern PHC accounts for both larger service catchments and anticipated demand increases, ensuring that improvements are sustainable rather than short-term. This capacity-based planning approach strengthens the relevance of the results for MoH-led infrastructure investment and PHC expansion strategies. Spatial autocorrelation analysis indicates that accessibility remains significantly clustered under both scenarios, suggesting that access patterns are strongly shaped by urban structure. However, the reduction in Moran's I under the proposed pattern indicates a decrease in clustering intensity, reflecting partial improvement in previously underserved areas rather than relocation of inequity. Similar outcomes have been observed in studies showing that targeted facility placement can reduce spatial access gaps without eliminating clustering entirely (Cheng *et al*., 2024).

Equity metrics further support these findings. Although the CV increased following the intervention, this reflects greater differentiation driven by improvements in low-access districts rather than worsening inequality. In contrast, the sharp decline in the P_{90}/P_{10} ratio demonstrates a substantial narrowing of extreme accessibility gaps. Tail-sensitive indicators show that B_{40} captured a larger share of total accessibility, while the share held by the T_{20} declined moderately. The reduction in the Gini coefficient and inward shift of the Lorenz curve confirm an overall improvement in equity. These results indicate that accessibility gains are primarily driven by improvements among underserved districts, without reducing access in already well-served areas.

From a policy perspective, the findings support Saudi MoH objectives aimed at reducing regional disparities and planning for future population growth. Assigning higher capacity to the proposed southern PHC reflects anticipated demand projection and larger catchment areas, ensuring that improvements are sustainable rather than achieving short term goals. Broadly, the integrated framework attempts to demonstrate how accessibility modelling, equity metrics, and scenario-based optimization can jointly inform long-term PHC expansion strategies, capacity prioritization, and investment planning. While data limitations remain, particularly regarding staffing levels, service quality, and temporal congestion, the approach provides a transferable, policy-relevant model for addressing spatial inequities in primary healthcare access across rapidly urbanizing contexts.

Conclusions

This study demonstrates that proximity-based measures substantially overestimate effective access to primary healthcare in rapidly growing cities such as Jeddah when population demand and facility capacity are not explicitly considered. Using a capacity-sensitive M2SFCA framework integrated with location–allocation modelling, the analysis reveals pronounced baseline inequities, with strong spatial clustering and severe upper–lower disparities in accessibility. Scenario-based expansion of PHCs aligned with Saudi Ministry of Health equity objectives produced measurable improvements: extreme inequality declined sharply from 81.34 to 9.13, overall inequality decreased from 0.191 to 0.172, and the accessibility share captured by the bottom 40% of the population increased, while concentration among the top 20% declined modestly. Although accessibility remained spatially clustered, the reduced Moran's I indicates weakening concentration and more balanced access across districts. Assigning higher capacity to southern facilities reflects a policy-relevant approach that accommodates both current service gaps and future population growth.

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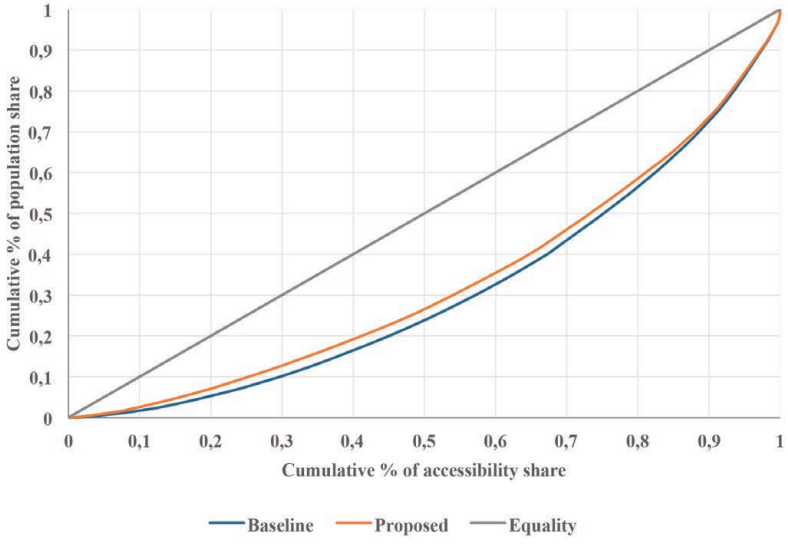

Figure 6. Lorenz curves of population-weighted accessibility for baseline and proposed scenarios.

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