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Spatial equity in healthcare accessibility for ageing populations: an enhanced two-step floating catchment area analysis in Antalya, Türkiye

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Abstract

Conventional spatial accessibility metrics treat the population aged 65 years and over as homogeneous, despite well-documented declines in mobility across age sub-groups that may conceal disadvantage affecting the oldest-old. This cross-sectional ecological study quantified age-stratified inequality in healthcare accessibility across the 19 districts of Antalya province, Turkey. An age-stratified, topographically-adjusted enhanced two-step floating catchment area (AT-E2SFCA) method was developed, incorporating age-specific catchment parameters for sub-groups aged 65–74, 75–84 and 85 years and over; decoupled sub-models for acute (hospital) and preventive (primary care) services; and a topographic correction of effective travel distance. Data on 44 hospitals, 295 family health centres, 17 dialysis centres, 8 oncology centres and 920 pharmacies were obtained from official registries. Inequality was assessed using Gini coefficients, global Moran's I and Local Indicators of Spatial Association (LISA); sensitivity analyses addressed both catchment parameters and the topographic correction. Aggregate measures for those aged 65 and over underestimated inequality affecting the oldest-old by 34% for acute care and 49% for preventive care. The acute Gini coefficient rose from 0.262 (aged 65–74) to 0.362 (aged 85 and over), approaching severe inequality, whereas the aggregate composite (0.271) remained moderate. Acute and preventive disadvantage patterns were partially independent. LISA identified a high-accessibility urban core and peripheral low-access districts. A 150-bed hospital scenario was equity-neutral and locally beneficial, whereas a 250-bed expansion mildly worsened inequality by concentrating capacity. Age-disaggregated, service-decoupled accessibility metrics are essential for equity-focused geriatric health planning; strategic facility siting, rather than undifferentiated capacity expansion, drives equity gains.

Key words: spatial accessibility; healthcare equity; ageing; oldest-old; floating catchment area; Turkey.

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Introduction

Population ageing is reshaping the demand for geriatric health services worldwide. By 2050, approximately 16% of the global population will be aged 65 years and over, with the oldest-old (defined here as those aged 85 years and over) growing fastest in most countries (United Nations, 2024). In Turkey, the population aged 65 and over exceeds 9.5 million (11.1%), with the oldest-old share reaching 18% in mountainous rural districts (TÜİK, 2025). Ensuring equitable geographic access to health services for this heterogeneous population is a central concern for health systems and for the social organisation of geriatric care (World Health Organization, 2015).

Geographic accessibility is a key determinant of care utilisation and health outcomes (Penchansky & Thomas, 1981; Wang & Luo, 2005). The Enhanced Two-Step Floating Catchment Area (E2SFCA) method (Luo & Qi, 2009) is the standard tool for measuring potential spatial accessibility. Subsequent refinements have introduced dynamic catchment sizes (McGrail & Humphreys, 2014), three-step extensions (Wan *et al.*, 2012), variable distance decay (Bauer & Groneberg, 2016) and elderly-focused applications (Cheng *et al.*, 2016; Luo *et al.*, 2018).

Despite this progress, three limitations persist in accessibility research on ageing populations. First, the population aged 65 and over is almost universally treated as homogeneous, despite evidence that mobility, driving capacity and care-seeking autonomy decline non-linearly across age sub-groups (Anstey *et al.*, 2005; Mollenkopf *et al.*, 2011; Webber *et al.*, 2010). Second, acute and preventive services have different access dynamics, yet most studies aggregate them (Currie *et al.*, 2021). Third, topographic friction reduces effective travel distance for older adults in mountainous regions but is rarely modelled (Tobler, 1993).

To our knowledge, few previous studies have simultaneously i) decomposed accessibility inequality by elderly age sub-group, ii) decoupled acute and preventive services within a single framework, and iii) incorporated a terrain correction, and then quantified how much conventional aggregate metrics conceal. This study addresses that gap by introducing an age-stratified, topographically-adjusted E2SFCA (AT-E2SFCA) method, applied to Antalya, Turkey, a province uniquely suited to this question. Antalya combines a dense urban core, a heavily populated Mediterranean tourism coast, and a sparsely populated Taurus alpine interior within a single administrative unit; district mean slope ranges twelvefold (2° to 20°), and the share of those aged 65 and over ranges from 8.5% to 31.5%. This coexistence of steep terrain, concentrated hospital capacity, and ageing rural populations makes within-province inequality both large and policy-relevant.

The primary objective is to test whether, and by how much,

aggregate accessibility metrics for those aged 65 and over conceal inequality affecting the oldest-old. Three hypotheses are tested: i) aggregate measures for those aged 65 and over conceal inequality affecting the oldest-old; ii) decoupled acute and preventive sub-models reveal distinct spatial patterns; and iii) capacity expansion alone does not necessarily improve spatial equity. A planned district hospital is further evaluated as a real-world scenario to demonstrate the framework's utility for geriatric health service planning.

Materials and Methods

Study design and setting

A cross-sectional ecological design was used across the 19 districts of Antalya province, south-western Turkey (2,777,677 residents; 20,177 km²). Mean district slope ranges from 2° (urban Muratpaşa) to 20° (alpine Gündoğmuş). Three districts form an urban core; five are tourism-intensive coastal districts; and three are alpine interior districts with shares of those aged 65 and over approaching 30% (TÜİK, 2025). An overview of the complete analytical workflow, from data collection to policy-relevant outputs, is presented in Figure 1.

Data sources

District population and proportions of those aged 65 and over were obtained from the Turkish Statistical Institute (TÜİK, 2025). Facility data (19 public, 22 private and 3 university hospitals; 295 family health centres; 17 dialysis centres; 8 oncology centres; and 920 pharmacies) were obtained from the Antalya Provincial Health Directorate and public databases. Inter-district road distances were obtained from Google Maps routing (May 2026); district mean slope was derived from Shuttle Radar Topography Mission 30-m elevation data (Farr *et al*., 2007).

Age sub-group populations (65–74, 75–84 and ≥85 years) were estimated by applying national age-distribution rates to each district's population aged 65 and over, adjusted by district character: mountainous and rural interior districts were assigned higher oldest-old shares, consistent with documented rural-longevity and youth out-migration patterns. Because these sub-group populations are modelled rather than directly observed, their uncertainty is examined explicitly in the sensitivity analysis and addressed in the Limitations.

The AT-E2SFCA method

The AT-E2SFCA framework extends the standard E2SFCA method (Luo & Qi, 2009) with three additions: age-specific catchment parameters, a topographic correction of travel distance, and decoupled acute and preventive sub-models. The full set of equations is given below (Equations 1–8). A comparable stepwise geospatial workflow has recently been applied to emergency cardiac care accessibility in Georgia, USA (Kianfar *et al.*, 2026), supporting the analytical structure adopted here.

Age-specific catchment parameters

For each age sub-group, distinct threshold distances (d_0) and Gaussian decay parameters (σ) were specified. Rather than applying a single catchment to all older adults, the parameters were graded to reflect documented age-related declines in travel range and driving autonomy (Mollenkopf *et al.*, 2011; Webber *et al.*, 2010): younger-old adults retain wider effective catchments, whereas the oldest-old are constrained to progressively tighter ones. For acute care, threshold distances of 75, 50 and 30 km were assigned to the 65–74, 75–84 and ≥85 groups respectively (σ = 35, 25, 15 km); these values approximate the referral-tolerant travel ranges reported for hospital-based care while halving the effective range between the youngest-old and oldest-old. Preventive catchments were set substantially tighter (d_0 = 15, 10 and 7 km; σ = 7, 5 and 3.5 km), reflecting the routine-proximity requirement of primary care. The robustness of results to these specific choices is assessed in the sensitivity analysis. It should be emphasised that these catchment values represent informed assumptions derived from the mobility literature rather than empirically validated thresholds; the sensitivity analysis therefore serves to bound, rather than to confirm, their exact specification.

Topographic correction

Effective travel distance was adjusted for terrain (Equation 1). A conservative linear slope penalty was adopted, whereby effective distance increases in proportion to mean path slope. This linear form was preferred over steeper impedance functions, such as Tobler's hiking function (Tobler, 1993), because it makes the most conservative assumption compatible with the direction of terrain effects, avoiding the larger penalties (and hence larger inequality estimates) that an exponential function would produce. To confirm that the central finding does not depend on this choice, the topographic correction was itself subjected to a sensitivity analysis comparing no correction, the linear penalty, and Tobler's function (see Results).

Decoupled acute and preventive sub-models

Two parallel sub-models were computed. The acute sub-model uses hospital beds as the capacity term, since acute geriatric care (inpatient treatment, emergency stabilisation, specialist referral) is bed-dependent and tolerates longer, referral-mediated travel. The preventive sub-model uses the family health centre count, since preventive and chronic-disease care for older adults (diabetes and hypertension monitoring, polypharmacy oversight, routine follow-up) depends on frequent, proximate contact rather than bed capacity. Treating these services separately allows service-specific disadvantage to be identified, which a single blended metric would obscure.

Computation and equations

The method was applied in the standard two steps (Luo & Qi, 2009). In the first step, a provider-to-population ratio was computed for each facility location (Equation 3); in the second, these ratios were summed across accessible facilities for each district, weighted by the age-specific Gaussian decay (Equation 4). Composite scores weighted age-specific accessibility by demographic share (Equation 5). Computations used Python 3.12; all code and processed data are openly available (see Data availability).

$$d_eff(i,j) = d(i,j) \times (1 + \hat{s}(i,j)/100) \quad (1)$$

where $d(i,j)$ is the road distance between districts i and j, and $\hat{s}(i,j) = (s_i + s_j)/2$ is the mean path slope (%).

$$G_g(i,j) = \exp(-d_eff(i,j)^2 / 2\sigma_g^2) \text{ if } d_eff \le d_0_g, \text{ else } 0 \quad (2)$$

where g denotes the age group; d_0_g and σ_g are the age-specific threshold distance and decay parameter.

$$R_j\hat{}g = S_j / \Sigma_k\, G_g(k,j) \cdot P_k\hat{}g \quad (3)$$

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Step 1: S_j is the service capacity at j (beds or ASM count); P_k^g is the group-g population of district k.

$$A_i^g = \Sigma_j G_{g(i,j)} \cdot R_j^g \quad (4)$$

Step 2: A_i^g is the accessibility score of district i for age group g (scaled per 100,000).

$$A_i^{composite} = \Sigma_g (P_i^g / P_i^{65+}) \cdot A_i^g \quad (5)$$

Composite accessibility, weighting age-specific scores by demographic share.

$$G = \Sigma_i \Sigma_j |A_i - A_j| / (2n^2\mu) \quad (6)$$

Gini coefficient; n = 19 districts, μ = mean accessibility. Thresholds: <0.2 low, 0.2–0.4 moderate, >0.4 high (Allison, 1978).

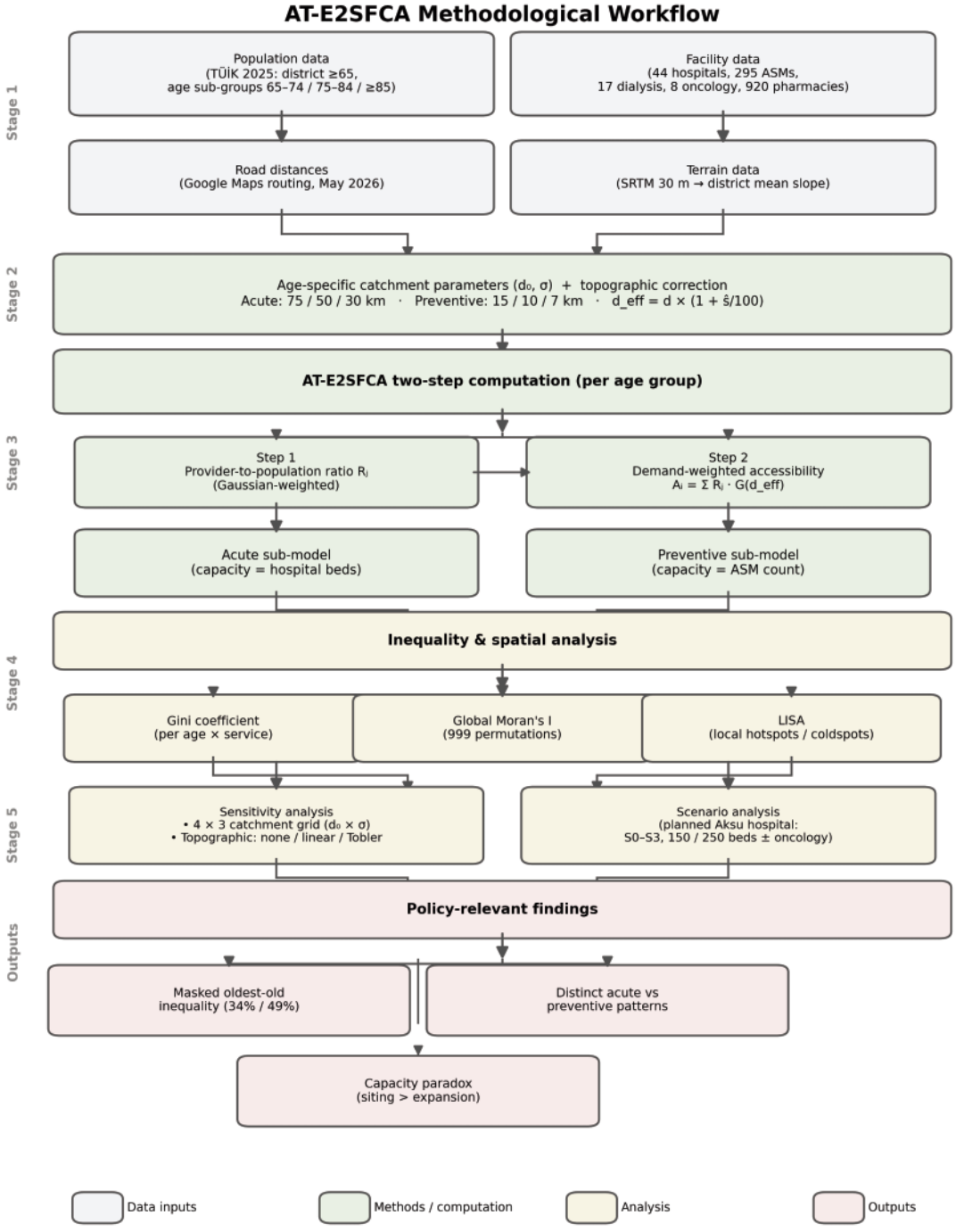


Figure 1. Methodological workflow of the AT-E2SFCA framework, from data collection through accessibility computation, inequality and spatial analysis, sensitivity and scenario testing, to policy-relevant outputs.

$$I = (n/\Sigma_i\Sigma_j w_{ij}) \cdot [\Sigma_i\Sigma_j w_{ij}(A_i-\bar{A})(A_j-\bar{A}) / \Sigma_i(A_i-\bar{A})^2] \quad (7)$$

Global Moran's I; w_{ij} is the spatial weights matrix, $\bar{A}$ the mean accessibility.

$$I_i = [(A_i - \bar{A})/m_2] \cdot \Sigma_j w_{ij}(A_j - \bar{A}) \quad (8)$$

Local Moran's I (LISA), where $m_2 = \Sigma_i(A_i-\bar{A})^2/n$. High-high and low-low values denote hotspots and coldspots respectively.

Spatial inequality and validation

Gini coefficients were computed for each age sub-group within each sub-model (Allison, 1978). Spatial autocorrelation was assessed using global Moran's I with 999 permutations (Anselin, 1995). To locate specific clusters rather than only confirm their presence, local indicators of spatial association (LISA; local Moran's I) were additionally computed, identifying significant high-high (hotspot) and low-low (coldspot) districts (Anselin, 1995). Sensitivity of the catchment for those aged 85 and over was tested across a 4 × 3 parameter grid (varying catchment parameters only, holding the decay function form constant).

Scenario analysis

Aksu district (population aged 65 and over ≈ 7,836) currently lacks a general hospital; one is scheduled to open in late 2026 or early 2027. Three configurations were simulated against the current baseline (S0): a 150-bed hospital (S1), a 250-bed expansion (S2) and a 150-bed hospital with an oncology unit (S3). Each scenario was modelled by adding the specified bed capacity to Aksu's facility term and recomputing acute accessibility for all districts, holding population, demand distribution, and referral behaviour constant; scenarios were compared on the ≥85 Gini coefficient and district-level access scores. These simplifying assumptions are stated explicitly to support reproducibility and are revisited in the Discussion.

Ethics

This study used exclusively publicly available, aggregated secondary data with no individual participants. Under Turkish research guidelines (Higher Education Council, 2019), such studies do not require institutional ethics committee approval.

Results

Population and infrastructure

The 19 districts contained an estimated 305,500 residents aged 65 and over (approximately 178,000 aged 65–74; 91,200 aged 75–84; and 36,300 aged 85 and over). Proportions of those aged 65 and over ranged from 8.5% (Kepez) to 31.5% (İbradı). Two urban hospitals held 35% of provincial bed capacity (Figure 2).

Masked inequality of the oldest-old

Aggregate measures underestimated inequality affecting the oldest-old by 34% for acute care and 49% for preventive care (Table 1). The acute Gini coefficient for those aged 85 and over (0.362) approached the high-inequality threshold, whereas the composite measure (0.271) remained moderate. The relative increase from those aged 65–74 to those aged 85 and over was steeper for preventive (+65%) than for acute (+38%) services (Figure 3).

Distinct acute and preventive patterns

Acute and preventive disadvantage patterns were partially independent. The most disadvantaged districts for acute access among those aged 85 and over were İbradı, Kaş, Gündoğmuş, Akseki and Serik. For preventive access, they were Gündoğmuş, Alanya, Akseki, İbradı and Kumluca, including Alanya, a coastal district whose family health centre network lags behind seasonal population growth (Figures 4 and 5). Single-metric planning would therefore misdiagnose need.

Spatial autocorrelation and local clusters

Global Moran's I for composite acute access confirmed significant positive spatial clustering ($p = 0.001$). To locate these clusters, local indicators of spatial association (LISA) were computed for acute access among those aged 85 and over (Figure 6). Four significant high-high hotspots were identified (Muratpaşa, Kepez, Konyaaltı and Döşemealtı), forming a contiguous high-accessibility urban core. One significant low-low coldspot (Manavgat) marked a zone of concentrated peripheral disadvantage. Several districts (Aksu, Serik, Kemer, Korkuteli) emerged as significant

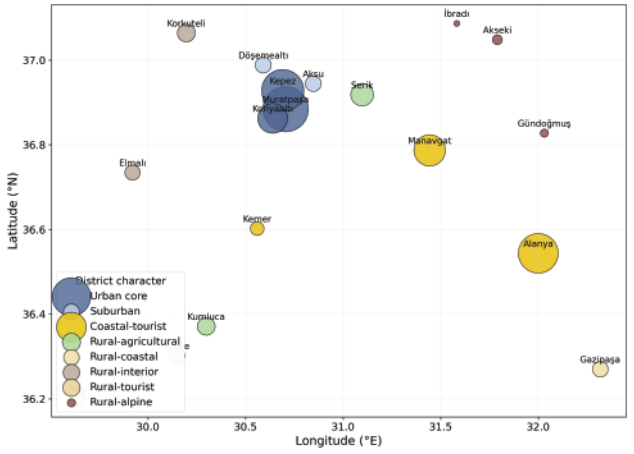


Figure 2. Study area: the 19 districts of Antalya province, Turkey. Circle size is proportional to the population aged 65 and over; colour indicates district character.

Table 1. Gini coefficients by age sub-group and service type.

Age sub-group (years)	Acute model	Preventive model	Interpretation
65–74	0.262	0.118	Moderate / Low
75–84	0.291	0.145	Moderate / Low
≥85	0.362	0.195	High / Low–moderate
Composite (≥65)	0.271	0.131	Moderate / Low

Gini thresholds: <0.2 low, 0.2–0.4 moderate, >0.4 high (Allison, 1978).

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low-high spatial outliers: districts of relatively low access bordering the high-access core, representing priority targets where disadvantage is masked by proximity to well-served neighbours.

Capacity paradox in the hospital scenario

Under the model assumptions, the 150-bed scenario (S1) raised acute access for those aged 85 and over in Aksu by 25.9% while leaving the ≥85 Gini coefficient essentially unchanged. The 250-bed scenario (S2) raised Aksu access by 43.2% but slightly increased the overall Gini coefficient, as capacity concentrated in a single suburban-proximate district widened the gap with far-peripheral districts (Table 2, Figure 7). The oncology-augmented scenario (S3) produced niche gains without altering general access. This "capacity paradox" is a model-based result, contingent on the stated assumptions of fixed demand and referral behaviour, and should be interpreted as a scenario illustration rather than a general planning rule; its policy reading is developed cautiously in the Discussion.

Sensitivity analysis

Two sensitivity analyses were conducted. Across the 4 × 3 catchment parameter grid, the Gini coefficient for acute access among those aged 85 and over ranged from 0.357 to 0.424, all at or above the moderate threshold; rank ordering was stable (Spearman's ρ > 0.93), confirming the robustness of the central finding (Figure 8). A second sensitivity analysis addressed the topographic correction itself (Table 3). The ≥85 acute Gini coefficient was 0.352 with no correction, 0.362 under the adopted linear penalty, and 0.416 under Tobler's hiking function. District rankings remained highly consistent across the three specifications (Spearman's ρ = 0.96 between no correction and linear; ρ=0.87 between linear and Tobler). The adopted linear penalty therefore yields the most conservative inequality estimate among the terrain-adjusted options, and the finding of elevated oldest-old disadvantage is not an artefact of the specific correction chosen.

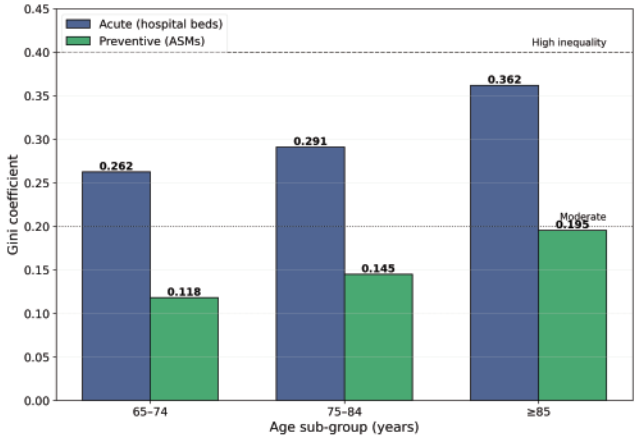


Figure 3. Age-stratified inequality in healthcare accessibility, by service type. Gini coefficients are shown for each age sub-group and for the acute and preventive models.

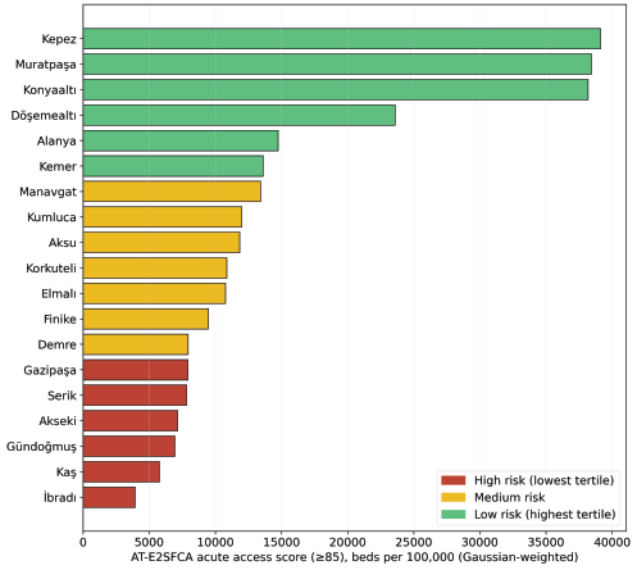


Figure 4. District-level acute care accessibility for those aged 85 and over, ranked by AT-E2SFCA score. Tertile-based risk classification: red, high risk; amber, medium; green, low.

Table 2. Scenario comparison for the planned district hospital (acute model, those aged 85 and over).

Scenario	Gini (≥85)	Δ Gini	Aksu access Δ	Equity implication
S0: current	0.362	—	—	Baseline
S1: 150 beds	0.362	−0.1%	+25.9%	Equity-neutral
S2: 250 beds	0.363	+0.4%	+43.2%	Mild worsening
S3: 150 + oncology	0.362	−0.1%	+25.9%	Niche gain

Δ indicates change relative to the S0 baseline.

Table 3. Sensitivity of the ≥85 acute Gini coefficient to the topographic correction.

Topographic correction	Gini (≥85 acute)	Spearman's ρ vs linear
None	0.352	0.96
Linear penalty (adopted)	0.362	—
Tobler's hiking function	0.416	0.87

District rankings remained highly consistent across specifications, confirming the finding is not an artefact of the correction chosen.

Discussion

This study demonstrates that conventional aggregate accessibility metrics for those aged 65 and over systematically conceal inequality affecting the oldest-old. The 1.38-fold (acute) and 1.65-fold (preventive) ratios between the Gini coefficients of those aged 85 and over and those aged 65–74 indicate that the oldest-old face fundamentally different access geographies from the young-old. This extends observations from Wuhan (Luo *et al.*, 2018) and other settings on the inadequacy of homogeneous-elderly assumptions; the present study is, to our knowledge, among the first to combine an explicit Gini decomposition by elderly age sub-group with service-type decoupling.

The reason aggregate metrics fail is mechanical but consequential. Because the oldest-old are concentrated in precisely the peripheral, mountainous districts where hospital capacity is thinnest, and because their narrower effective catchments exclude the distant urban hospitals that inflate the access scores of younger-old adults, their disadvantage is both real and structurally hidden. Averaging across the 65-and-over group allows the wide catchments of the young-old to mask it. The LISA results make this spatial structure concrete: the high-high cluster coincides exactly with the three-district urban core, while the low-high outliers (Aksu, Serik, Kemer and Korkuteli) reveal districts whose own access is poor despite bordering the well-served core, a pattern that province-level averages would entirely miss.

Decoupling acute and preventive services reveals distinct access regimes. Acute access shows higher absolute inequality (reflecting hospital concentration) but a moderate age gradient, whereas preventive access shows lower absolute inequality (reflecting the dense ASM network) but a steeper age gradient. This divergence matters for planning: a district may appear adequately served on one dimension while being critically underserved on the other. Alanya illustrates this: its acute access is unremarkable, but its preventive access ranks among the worst, because its family health centre network has not kept pace with

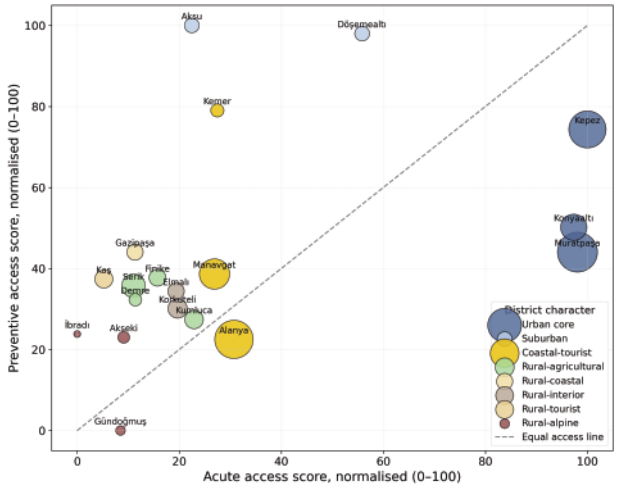


Figure 5. Decoupled acute and preventive access, showing partially independent disadvantage patterns across districts. The diagonal represents equal access on both dimensions.

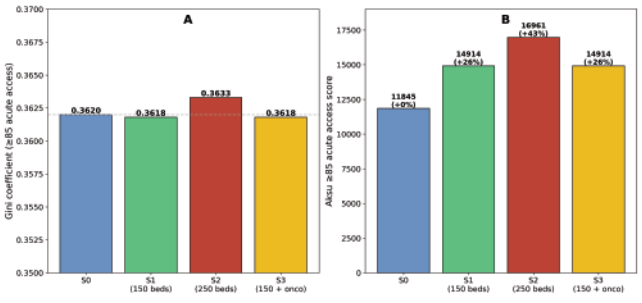


Figure 7. Capacity paradox in the planned Aksu hospital scenario. Panel A, the ≥85 acute Gini coefficient; panel B, Aksu local access, across scenarios S0–S3.

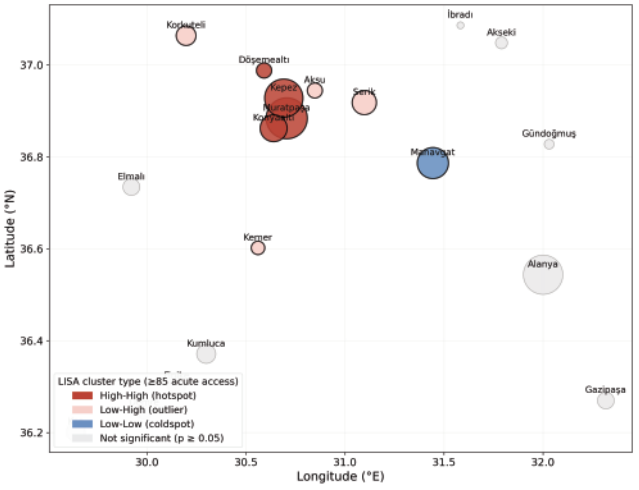


Figure 6. Local indicators of spatial association (LISA) for acute access among those aged 85 and over. High-high hotspots form the urban core; the low-low coldspot and low-high outliers mark peripheral disadvantage. Circle size is proportional to the population aged 85 and over.

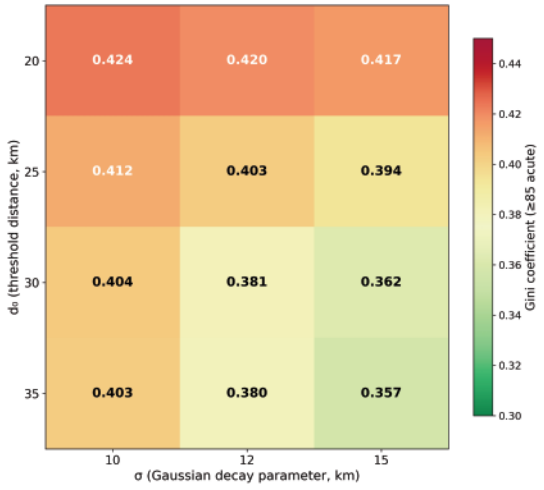


Figure 8. Sensitivity analysis of the ≥85 acute access Gini coefficient across a 4 × 3 parameter grid (d_0 × σ), confirming robustness.

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rapid coastal and seasonal population growth. Because family health centres cannot be substituted by hospitals for chronic-disease management (Penchansky & Thomas, 1981), single-metric planning would misdirect investment.

These findings translate into concrete options for geriatric health planning. For the peripheral coldspot and low-high outlier districts, where building full hospitals is neither affordable nor equity-optimal, the more effective levers are likely to be mobile health units and periodic specialist outreach to reach frail, transport-dependent oldest-old residents; telehealth-enabled chronic-disease monitoring to compensate for sparse preventive infrastructure; strengthening of the family health centre network in demand-outpaced districts such as Alanya; and transport or patient-navigation support that shortens the effective distance frail older adults must travel. Within the limits of the model, the scenario analysis is consistent with this direction: strategic siting and service mix, rather than undifferentiated capacity, appear to drive equity gains.

The scenario analysis shows that uncritical capacity expansion does not equalise access. The 150-bed configuration is equity-neutral and locally beneficial, whereas the 250-bed expansion mildly worsens inequality by concentrating capacity. This result should be read with appropriate caution. It is a model-based scenario resting on fixed-demand and fixed-referral assumptions, not an empirical outcome; it does not imply that a larger hospital is undesirable in absolute terms, only that, under these assumptions, additional beds concentrated in one suburban-proximate district do not improve, and may marginally worsen, the province-wide distribution for the oldest-old. The practical implication is that the equity consequences of siting decisions warrant explicit modelling, not that capacity should be withheld.

Several interpretive cautions apply. The framework measures potential spatial accessibility, the configuration of supply relative to where older adults live, not realised utilisation, health-seeking behaviour, or health outcomes. High modelled access does not guarantee use, nor does low access by itself establish unmet need. Accordingly, the policy implications above should be understood as hypotheses for locally informed planning rather than as direct prescriptions.

Limitations

Several limitations should be acknowledged. First, district-level analysis cannot resolve within-district heterogeneity; neighbourhood-level integration using gridded population data is planned. Second, age sub-group populations were modelled from national distributions adjusted by district character rather than observed at district level, which is an important source of uncertainty; although the sensitivity analysis shows the central finding to be robust to parameter variation, directly observed sub-group counts would strengthen future work. Third, accessibility was based on road distances between district centroids, which may not capture real travel time, within-district variation, seasonal road conditions in mountainous areas, or public-transport availability, factors particularly relevant to the frail oldest-old, who often depend on caregivers for transport. Fourth, the data do not distinguish public from private provision, and differences in affordability, insurance coverage, service quality, provider availability, and appointment capacity between these sectors were not modelled; all facilities were treated as equally accessible, which may overstate effective access where private capacity dominates. Fifth, the study measures potential, not realised, accessibility (Penchansky & Thomas, 1981).

Conclusions

This study shows that measuring healthcare accessibility for older adults with a single, aggregate metric can systematically obscure the disadvantage experienced by the oldest-old, who face distinct access geographies shaped by frailty, terrain and the differing logics of acute and preventive care. The principal contribution is methodological: an age-disaggregated, service-decoupled and terrain-aware framework that makes such hidden inequality visible and locates it spatially. For geriatric health service planning, the findings underline that equity depends less on how much capacity is added than on where and how services are configured relative to the populations most constrained in reaching them. Future work should extend the framework to finer spatial resolutions using gridded population data, incorporate directly observed age-specific populations and realised utilisation, and test its transferability across other geographically heterogeneous settings. To support such extensions, the full analysis code and data are openly available.

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