Geospatial Health 2025; volume 20:1414

pagepress

Promoting sustainable health equity: accessibility analysis and optimization of tertiary hospital networks in China's metropolitan areas

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Abstract

Healthcare accessibility is vital for sustainable urban development, ensuring timely diagnosis, chronic disease management, and emergency response. However, in many developing countries, the uneven distribution of advanced healthcare services exacerbates health disparities. Taking Tianjin in China as an example, this study aims to evaluate the spatial accessibility of tertiary hospitals and optimize hospital placement to improve healthcare coverage. Using the Gaussian Two-Step Floating Catchment Area (G2SFCA) method, the study integrated high-resolution spatial data on hospital locations, population density, and transportation networks, assessing the accessibility of higher-level healthcare services citywide. The results indicate that central urban districts exhibited high accessibility, where all demand points were within the 1-hour service range. In contrast, suburban districts had an average accessibility of 0.194, and outer suburban districts had the lowest citywide mean of 0.005, with less than 20% of the area covered. Despite its economic significance, Binhai New Area's healthcare accessibility remained inadequate, with a mean score of 0.010. The application of a location-allocation model to optimize the placement of 24 planned new hospitals, prioritizing areas with high population density and low accessibility resulted in an increased population coverage from 73.31% to 95.05%, significantly reducing non-accessible points. This study aligns with the United Nations' Sustainable Development Goals 3 and 11, advocating a hierarchical healthcare system, telemedicine, and improved transportation to minimize time costs and reduce inequities.

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Key words: healthcare accessibility, location optimization, tertiary hospitals, Gaussian two-step floating catchment area method, health equity, China.

Conflict of interest: the authors declared no potential conflict of interest with respect to the research, authorship and/or publication of this article.

Funding: this work was supported by the Hainan Provincial Natural Science Foundation of China [724QN233]and the Graduate School of Tianjin University [A1-2021-009] and the Hainan Provincial Philosophy and Social Science Planning Project [hnsz2025-14].

Contributions: JH, methodology, data collection and processing, writing - original draft; TP, methodology, formal analysis; LF, formal analysis, validation; TZ, data collection and processing.

Data availability statement: the data used in this study are all publicly available. Hospital location data were obtained from the Gaode Open Platform's Point of Interest (POI) database (https://lbs.amap.com/api/webservice/guide/api-advanced/search). Population data were sourced from the WorldPop dataset (https://hub.worldpop.org/geodata/summary?id=49730), and road network data were collected from OpenStreetMap (https://www.openstreetmap.org/node/244082077#map=11/39.1177/117.1913). All datasets can be freely accessed through their respective platforms.

Received: 24 June 2025.
Accepted: 16 August 2025.

Geospatial Health 2025; 20:1414
doi:10.4081/gh.2025.1414

Introduction

Accessibility to healthcare has long been a central focus (Neutens, 2015), directly influencing early disease diagnosis, chronic disease management and emergency responses (Tan *et al.*, 2019; Luo *et al.*, 2022; McElfish *et al.*, 2023). It also serves as a critical indicator of healthcare equity (Wang & Jia, 2021). In many countries, particularly in developing regions, healthcare resources are unevenly distributed, placing residents in remote areas at higher health risk (Martínez, 2021; Isnan *et al.*, 2025). In major Chinese cities, the driving time to tertiary hospitals for residents in the outermost areas is more than three times longer than the citywide average (Cheng *et al*., 2016). These disparities can delay treatment and limit access to preventive services (Song *et al.*, 2018; Rocque *et al.*, 2019), ultimately worsening socio-economic inequality and health outcomes (Kelly *et al.*, 2016; Guo *et al.*, 2024). Tertiary hospitals are the backbone of China's healthcare system, responsible for managing complex and critical conditions, medical education, and scientific research (Zhang *et al.*, 2018). In recent years, their number and service capacity have steadily expanded in response to growing health demand. By 2023, China had 3,855 tertiary hospitals, accounting for over one-third of all hospital beds and nearly half of in-patient services nationwide (National Health Commission of China, 2024). These hospitals play a central role not only in routine clinical care but also in major public health crises—for example, they treated more than

80% of severe COVID-19 cases. However, the spatial distribution of tertiary hospitals remains concentrated in urban centres, with peripheral regions facing considerable service gaps (Zhao *et al.*, 2020; Xing & Ng, 2022). This imbalance not only reduces the efficiency of resource utilization but also exacerbates regional disparities in healthcare access.

Broader structural trends have further intensified this imbalance between healthcare supply and demand. China's urbanization rate rose from 54.5% in 2013 to 66.2% in 2023 (National Bureau of Statistics of China, 2024), but the expansion of tertiary hospitals has disproportionately occurred in central districts with stronger infrastructure and economic capacity (Liu *et al.*, 2019; Qin *et al.*, 2024; Lee *et al.*, 2025). Peripheral areas have seen slower investment in high-level services, contributing to long-standing service gaps. In parallel, the aging of the population is reshaping healthcare demand (Li *et al.*, 2020). By 2023, the proportion of individuals aged 60 and above in China reached 21.1% (National Working Commission on Aging of China, 2024), with this demographic relying significantly more on tertiary hospitals than other age groups, particularly for chronic disease management and multimorbidity treatment (Franke *et al.*, 2012; Zhou *et al.*, 2021). Therefore, an effectively plan for the spatial distribution of tertiary hospitals to meet these multi-level needs has become a key issue that needs urgent attention.

Research has shown that data-driven and quantitative models for accessibility evaluation are crucial for identifying service gaps and guiding resource allocation (Gesler, 1986; Neutens, 2015). Traditional methods, such as distance buffers and gravity models, offer basic spatial insights but often oversimplify transportation dynamics and demand competition (Ingram, 1971; Geurs & Van Wee, 2004; Guagliardo, 2004). The Two-Step Floating Catchment Area (2SFCA) method addresses these limitations by incorporating both supply and demand within a two-step framework (Luo & Wang, 2003; Stacherl & Sauzet, 2023). To further enhance its accuracy, variants such as the Enhanced 2SFCA (E2SFCA), Multi-Modal 2SFCA (MM2SFCA) and Time-Sensitive 2SFCA (TS2SFCA) have been developed to reflect distance decay, transport modes, and temporal variability (Langford *et al.*, 2016; Ma *et al.*, 2018; Li & Wang, 2022). Building on this, the Gaussian 2SFCA (G2SFCA) introduces nonlinear decay weights, improving the model's sensitivity to real-world spatial patterns (Dai, 2010).

Tianjin, one of China's municipalities directly under the central government in the North, had a permanent population of approximately 13.64 million in 2023, with an urbanization rate of 85.5% (Tianjin Municipal Bureau of Statistics, 2024). The city boasts abundant high-quality medical resources, supported by a multi-tiered healthcare system centreed on 57 tertiary hospitals. With a rapidly aging population and increasing cross-regional healthcare demand, ensuring a rational spatial distribution of tertiary hospitals has become increasingly critical. Recent studies on healthcare accessibility in China have expanded but largely focused on the national scale or mega-cities such as Beijing and Shenzhen (Lu *et al.*, 2019; Wei *et al.*, 2022; Chen, Zeng, *et al.* 2023, with limited attention to emerging first-tier cities like Tianjin. Furthermore, many studies employ oversimplified approaches, such as using averages to measure healthcare supply and demand or considering travel distance alone as the accessibility metric (Chen, Zeng, *et al.* 2023). Lastly, most research evaluates accessibility without addressing strategies for optimizing resource allocation (Cheng *et al.*, 2016; Li & Wang, 2022). This study aims to fill these gaps to some extent.

This study evaluated the accessibility of tertiary hospitals in Tianjin within a one-hour travel time threshold and identified optimal locations for 24 proposed new tertiary hospitals to improve service coverage. The objective was to reduce barriers between residents and tertiary hospitals, fostering more equitable access to high-quality healthcare services in Tianjin.

Materials and Methods

We employed the G2SFCAmethod to assess accessibility, incorporating hospital bed capacity, population demand, and the actual road network. The analysis utilized high-resolution population data from the WorldPop dataset (https://www.worldpop.org/), road network data from OpenStreetMap (https://www.openstreetmap.org/), and tertiary hospital location data from the Gaode Open Platform (https://lbs.amap.com/). To pinpoint underserved areas, we examined service area boundaries alongside accessibility results and population density, selecting regions with low accessibility and high population density as candidate locations for new hospitals. A location-allocation analysis was then performed to determine the optimal placement of the 24 proposed hospitals, with the goal of maximizing population coverage.

Study area

Tianjin, located within the Haihe River Basin in northern China, is bordered by the Bohai Sea to the East, the Yanshan Mountains to the North, and the northern China Plain to the South. As one of China's four municipalities directly under the central government, Tianjin covers an area of 11,966 km^2 and is divided into 16 administrative districts. These districts are categorized into four categories: i) central urban districts, including Heping, Hedong, Hexi, Nankai, Hebei and Hongqiao; ii) suburban districts, including Dongli, Xiqing, Jinnan and Beichen; iii) Binhai New Area; and iv) outer suburban districts, including Wuqing, Baodi, Ninghe, Jinghai and Jizhou.

Tianjin's permanent population was 13.64 million in 2023,, with an urbanization rate of 85.5%. The city's Gross Domestic Product (GDP) reached 1.67 trillion Chinese yuan (RMB) (Tianjin Municipal Bureau of Statistics, 2024), a sum corresponding to about 228 billion USD. Over decades of development, Tianjin has established a relatively comprehensive healthcare system, including 57 tertiary hospitals, primarily concentrated in the central urban districts, while peripheral areas have fewer facilities.

Data

Hospital data

Tertiary hospitals are the core institutions providing high-quality comprehensive healthcare, offering essential medical services to Tianjin residents while also attracting patients from surrounding regions. The location data for these hospitals was obtained from the Gaode Open Platform's Point of Interest (POI) database, which provides latitude and longitude of each hospital. Referring to the studies by Li and Wang (2022) and Pan *et al.* (2023), this study used the total number of hospital beds in each tertiary hospitalas the indicator of healthcare resource supply, as it directly reflects a hospital's intake capacity and service potential. The data were provided by Tianjin's Municipal Health Committee.

As of 2023, Tianjin hosts 57 tertiary hospitals with a combined total of over 50,000 beds, averaging approximately 900 beds per hospital. However, significant disparities exist in the regional distribution of these beds, with more than 60% concentrated in the central urban districts. The spatial distribution and bed information of these hospitals are illustrated in Figures 1a and 1b.

Population data

This study utilized the 2020 gridded population data from the WorldPop dataset, which offers a spatial resolution of 100 meters, providing detailed insights into the spatial population distribution. To ensure consistency with the most recent official demography figures, the raster data were adjusted using correction factors calculated from the *China Statistical Yearbook 2024*, which reports population data for 2023. The population density of each district is illustrated in Figure 1c.

To address potential uneven population distributions or spatial omissions caused by traditional administrative boundaries, Tianjin was divided into 4 km^2 hexagonal grid cells. After excluding uninhabited grids, 5,429 valid grids were retained, and corrected population data within each valid grid were aggregated to generate demand indicators. The geometric centre of each grid was then defined as a demand point, with latitude and longitude coordinates extracted for subsequent accessibility analysis.

Travel data

To evaluate the actual travel time from demand points to tertiary hospitals in Tianjin, this study utilized 2023 road network data from OpenStreetMap. This dataset includes the geometry, road types and topological structure, offering the advantages of openness and extensive coverage. To align with Chinese road standards and traffic conditions, this study reclassified OpenStreetMap road types into six categories, as shown in Figure 1d. The travel speeds for each road type were assigned based on the *Design Specifications for Highway Speed Limit Signs of China* (JTG/T 3381-02—2020) and relevant studies (Wei *et al.*, 2022; Chen *et al.*, 2023) as detailed in Table 1. Compared to travel distance, actual travel time better reflects the impact of road conditions and traffic efficiency on hospital accessibility. Additionally, different levels of healthcare institutions have varying service capacities and attraction thresholds. Planning documents such as the "Healthy China 2030" strategy and municipal health guidelines for cities like Chengdu and Shanghai explicitly emphasize the goal of enabling residents to reach tertiary hospitals within one hour for critical and complex care needs. This "one-hour medical service circle" has become a widely accepted benchmark for China's urban health planning. Moreover, prior empirical studies have also adopted the one-hour threshold to evaluate spatial accessibility to tertiary hospitals in large metropolitan settings (Gu et al., 2019; Sun *et al.*, 2024). Consistent with these national objectives and methodological precedents, this study adopted a 1-hour travel time as the threshold for tertiary hospital accessibility to ensure policy relevance and facilitate cross-regional comparability.

Statistical approach

This study employed the G2SFCA method to evaluate the accessibility of tertiary hospitals in Tianjin. This method integrates healthcare supply, population demand, and actual travel time, incorporating Gaussian weights into the distance decay function. This enhancement enables to more accurately capture the nonlinear impact of distance on accessibility compared to traditional approaches (Lu *et al*., 2019; Wei *et al*., 2022).

The first step calculated the service capacity R_j of each tertiary hospital, representing its relative ability to provide advanced medical services within its service area. The formula used was:

$$R_j = \frac{S_j}{\sum_{i \in T(d_{ij} \le d_0)} D_i W(d_{ij})} \quad \text{(Eq. 1)}$$

where S_j represents the total number of beds in the tertiary hospital; D_i the population demand at demand point i (*i.e.* the total population within each valid hexagonal grid); $W(d_{ij})$ the distance decay weight (indicating that the service capacity diminishes as travel time d_{ij} increases); and d_0 the travel time threshold (set at 60 minutes in this study) used to define the service area.
The second step calculated the accessibility A_i for each demand point, which represents the ability to access tertiary hospital resources within the service area, based on the formula:

$$A_i = \sum_{j \in T(d_{ij} \le d_0)} R_j W(d_{ij}) \quad \text{(Eq. 2)}$$

where d_0 is the travel time threshold; d_{ij} the travel time between demand point i and all tertiary hospitals within the service area; R_j each hospital's supply capacity, with the Gaussian weight $W(d_{ij})$ ensuring that hospitals with shorter travel times contribute more significantly to the accessibility of demand point i, while the influence of more distant hospitals gradually diminishes. By summing the service capacities R_j of all hospitals, the overall accessibility A_i was obtained, quantifying the spatial convenience and adequacy of accessing medical resources from each demand point.

The Gaussian distance decay weight $W(d_{ij})$ was defined as:

$$W(d_{ij}) = \begin{cases} \exp\left(-\frac{1}{2}\left(\frac{d_{ij}}{d_0}\right)^2\right) - \exp\left(-\frac{1}{2}\right), & \text{if } d_{ij} \le d_0, \\ 0, & \text{if } d_{ij} > d_0. \end{cases} \quad \text{(Eq. 3)}$$

where serves as a correction factor. When $d_{ij} \le d_0$, the weight decreases nonlinearly as the distance increases, while for $d_{ij} > d_o$, the weight becomes 0, indicating that supply-demand interactions beyond the travel time threshold are excluded. The nonlinear characteristics of the Gaussian weight effectively capture the progres-

Table 1. Classification of road types and corresponding travel speeds.

Road classification	Speed (km/h)
Motorway	75
Trunk	50
Primary road	40
Secondary road	20
Tertiary road	20
Other	15

sive impact of distance on healthcare access, aligning the model with real-world spatial dynamics.

According to the Tianjin Medical and Health Institution Layout Plan (2015-2035), the city plans to establish 83 tertiary hospitals by 2035, a goal requiring the construction of 24 new hospitals in addition to the existing facilities (Tianjin Health Commission, 2020). To optimize the locations of these new hospitals, this study employed a location-allocation analysis with the objective of maximizing the service coverage area of the additional tertiary hospitals. By integrating data on the distribution of existing

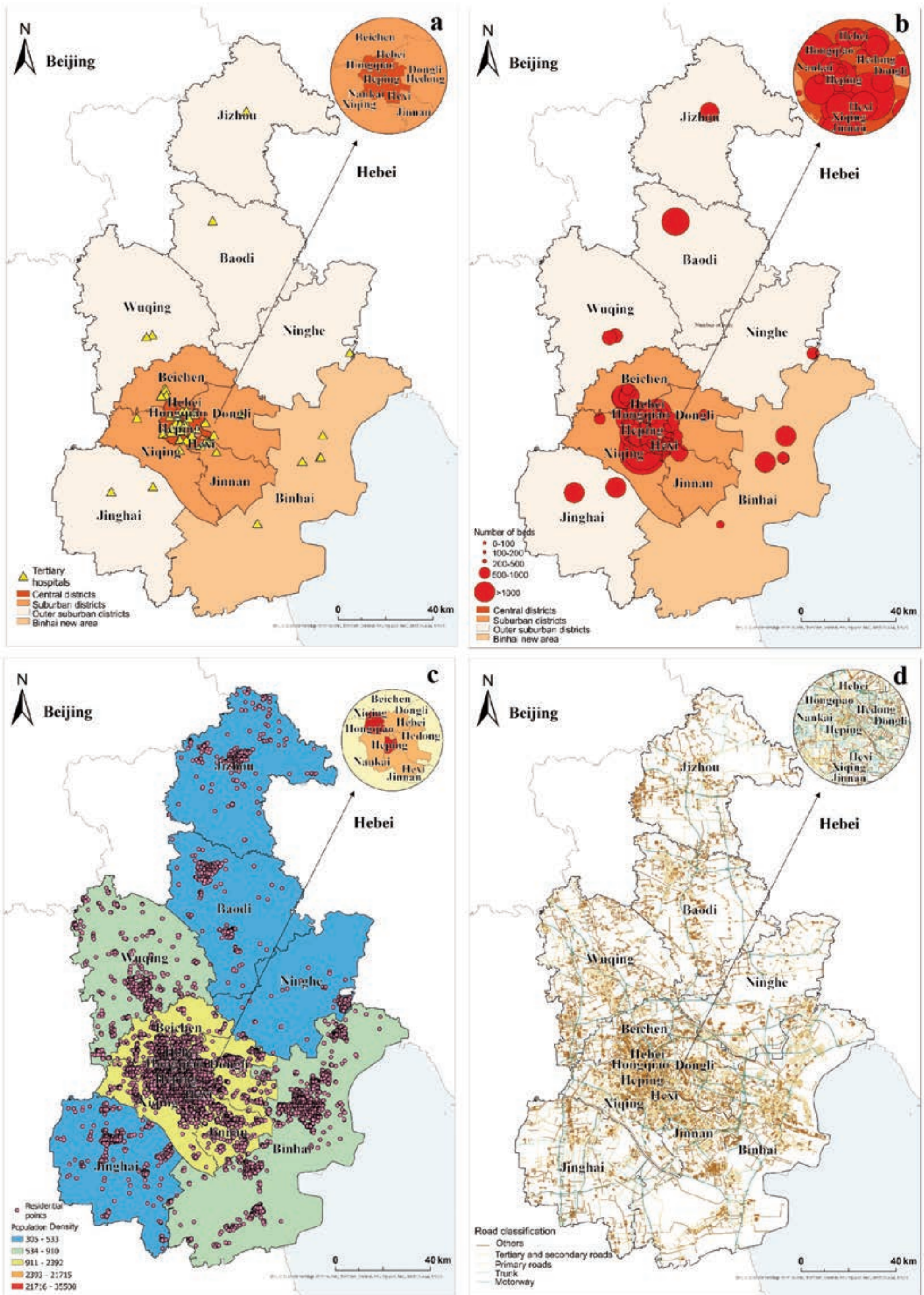

Figure 1. Spatial distribution of tertiary hospital, tertiary hospital beds, residential points, and road networks in Tianjin.

hospitals, population density, and accessibility, the method identified the optimal locations for the new hospitals that could significantly improve residents' access to high-quality healthcare services. For this reason, this study aimed to optimize the site selection for the newly planned tertiary hospitals in Tianjin based on accessibility results.

The optimization objective of the analysis was to maximize the population covered by the new tertiary hospitals. Specifically, the method defined the coverage status of each demand point to determine whether it fell within the service area of the new hospitals. The coverage status of a demand point was defined as:

$$C_i = \begin{cases} 1, & \text{if } d_{ij} \le T_{\max} \text{ for any } j \in F, \\ 0, & \text{otherwise.} \end{cases} \qquad \text{(Eq. 4)}$$

where x_{ij} represents the coverage status of the demand point i; d_{ij} the travel time between demand point i and the candidate facility j, with T_{max} the service range threshold (also set at 60 minutes) and F the set of all candidate facility locations. A demand point would be considered covered (C_i=0) if it falls within the service range of at least one candidate facility; otherwise, it remains uncovered (C_i=0). The optimization objective to maximize the covered population can be expressed as:

$$\max \sum_{i \in D} P_i \cdot C_i \qquad \text{(Eq. 5)}$$

where P_i represents the population at demand point i; and D the set of all demand points. This objective function prioritizes the selection of candidate facilities that maximize the population coverage, particularly in underserved regions.

The optimization model incorporates three key constraints: i) the fixed number of new facilities; ii) the allocation of demand points within service ranges; and iii) the requirement for unique allocations as outlined by equations 6-8 below:

$$\sum_{j \in F} y_j = 24 \qquad \text{(Eq. 6)}$$

$$x_{ij} \le y_j, \quad \forall i \in D, j \in F \qquad \text{(Eq. 7)}$$

$$\sum_{j \in F} x_{ij} = 1, \quad \forall i \in D \qquad \text{(Eq. 8)}$$

The first constraint guarantees that exactly 24 new tertiary hospitals are selected, where is a binary decision variable indicating whether candidate facility j is selected (y_j=1) or not (y_j=0). The second constraint restricts demand points to be assigned only to candidate facilities within their service range, where x_{ij} represents whether demand point i is assigned to candidate facility j. The third constraint ensures unique assignment by requiring each demand point to be allocated to exactly one facility.

Finally, we constructed a shortest travel time matrix $D=\{d_{ij}\}$ using OpenStreetMap data and applied an iterative process to identify the optimal solution by selecting the 24 combinations that maximized the population coverage.

The coverage effect of newly added tertiary hospitals can be evaluated by the final formula shown below:

$$\Delta C = \frac{\sum_{i \in D} P_i \cdot C_i^{\text{new}}}{\sum_{i \in D} P_i} - \frac{\sum_{i \in D} P_i \cdot C_i^{\text{existing}}}{\sum_{i \in D} P_i} \qquad \text{(Eq. 9)}$$

where C_i^{new} and $C_i^{existing}$ represent the coverage status of demand point i by the newly established hospital and the existing ones, respectively. A value of 1 indicates coverage of the demand point, while 0 indicates none. ΔC captures the extent at which the establishment of the new hospital enhances the overall population coverage rate. All spatial analyses were conducted using ArcGIS 10.6.1.

Results

Descriptive statistics

As of 2023, Tianjin had a total of 57 tertiary hospitals, with a combined capacity of 51,583 beds, averaging 905 beds per hospital (Table 2). The distribution of high-level medical resources in Tianjin is uneven, exhibiting a descending order from the central urban districts to suburban districts, outlying districts and Binhai New Area. Thus, the former districts house the majority of resources, with 34 tertiary hospitals accounting for 59.7% of the city's total and 32,172 beds, representing 62.4% of the total bed capacity of the area. Among these, Hexi District has the highest number of tertiary hospitals, with 9 facilities providing a total of 9,952 beds. In contrast, the outlying districts collectively had only 7 tertiary hospitals, making up 12.3% of the total, with 6,236 beds or 12.1% of the total capacity, facts that show the current, significant disparities in medical resource allocation.

On the demand side, Tianjin's population continues to grow, with the top three high-density areas being Heping, Nankai and Hebei districts, where the population densities in 2023 were 35,500.00, 21,715.17 and 21,590.07 per km², respectively. These districts collectively accounted for 8.0%, 14.6%, and 10.4% of the city's total tertiary hospital bed capacity. In contrast, the outlying districts, characterized by low population densities, has limited high-level medical resources. Among these, Ninghe, Baodi, and Jizhou districts, which ranks lowest in total population, each have only one tertiary hospital, which means that the coverage of medical resources is obviously insufficient. Additionally, there is an obvious mismatch between economic development and medical resources in Binhai New Area. Despite contributing a GDP of 730.30 billion RMB (just above 100 billion USD), accounting for 44.1% of the city's total, it is served by only 5 tertiary hospitals.

Accessibility of tertiary hospitals in Tianjin

This study evaluated the accessibility of 57 tertiary hospitals in Tianjin using the G2SFCA method. The results showed a mean accessibility value of 0.429, with significant spatial disparities across districts. As shown in Figures 2 and 3, the central urban districts demonstrated the highest accessibility, with values all exceeding 0.8. At 1.221, Heping District ranked the highest, followed by Hedong District (1.052) and Nankai District (1.030). All six central districts had a non-accessibility point proportion of 0%, reflecting the high concentration of advanced healthcare resources and superior spatial coverage within these areas. In contrast, the suburban districts showed lower accessibility, with an overall mean of 0.194. Among these, Beichen, Dongli, Jinnan and Jinghai districts recorded accessibility values of 0.238, 0.230, 0.196 and 0.111, respectively, with non-accessibility point proportions ranging from 18% to 27%.

The accessibility of Binhai New Area (0.010) was found to be between that of the suburban and outer suburban districts, falling short of expectations given its economic standing. Moreover, the outer suburban districts had the lowest accessibility citywide, with an overall mean of only 0.005 and a coverage rate below 20%. Ninghe (0.001) and Jizhou (0.002) were particularly under-resourced, with non-accessibility point proportions reaching 86.4% and 88.8%, respectively. Most demand points in these areas fell into zones with low accessibility or none at all, as indicated by large light blue areas in Figure 3. Overall, the distribution of tertiary hospital resources in Tianjin revealed a clear gradient, with availability decreasing from central urban districts to the outer suburban areas.

Location optimization of tertiary hospitals in Tianjin

Building on accessibility results, remotely sensed imagery and population density data, we next conducted a service area analysis to calculate the 1-hour travel time service range of existing tertiary hospitals. Figure 4a shows that the tertiary hospitals existing in 2023 covered 29.8% of Tianjin's total area and 73.3% of its population. The service areas were primarily concentrated in central urban districts and parts of suburban districts, with outer suburban districts and certain areas in Binhai New Area experiencing significant coverage gaps leaving most demand points outside the 1-hour service range. To address these gaps, we applied Zonal Statistics to identify densely populated but poorly accessible areas as target regions for new tertiary hospitals. As shown in Figure 4b, this process generated 3,616 candidate points in low-accessibility areas. We further refined these points manually, considering terrain features, to ensure their optimal placement in high-demand regions.

According to the Tianjin Medical and Health Institution Layout Plan (2015–2035), the city aims to establish 83 tertiary hospitals by 2035, requiring the addition of 24 hospitals to the existing 57 hospitals (Tianjin Health Commission, 2020). To support this objective, we conducted a location-allocation analysis to maximize population coverage, ultimately selecting 24 optimal locations from a pool of 3,616 candidate points. The optimal distribution of the new hospitals across administrative districts found to be 6 hospitals each in Binhai New Area and Jizhou District; 4 hospitals each in Wuqing and Ninghe districts; and 2 hospitals

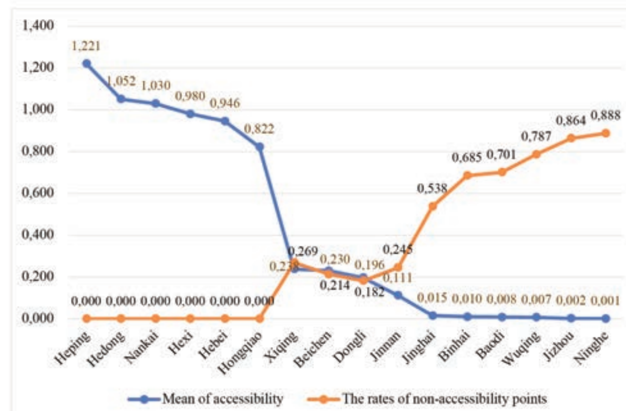

Figure 2. Spatial distribution of tertiary hospital accessibility and non-accessibility rates in Tianjin.

Table 2. Supply and demand of Tianjin' tertiary hospitals in 2023.

Classification	District	Annual GDP (CNY - USD)*	GDP growth rate (%)	Population density (per km²)	Average number of beds	Total number of beds	Number of tertiary hospital
Central urban district	Heping	670.76-93.42	4.5	35,500.00	518	4145	8
	Nankai	752.86-104.86	4.6	21,715.17	1073	7508	7
	Hebei	388.64-54.13	3.2	21,590.07	1072	5360	5
	Hedong	497.50-69.29	4.5	21,469.68	899	2697	3
	Hexi	1,154.20-160.75	4.4	17,128.63	1106	9952	9
	Hongqiao	198.41-27.63	8.1	20,130.42	1255	2510	2
Suburban district	Beichen	735.88-102.49	4.0	1,902.18	911	4555	5
	Jinnan	575.34-80.13	3.9	2,392.42	905	1810	2
	Dongli	720.67-100.37	3.1	1,796.69	500	1000	2
	Xiqing	1,004.10-139.85	3.3	2,114.64	1250	2500	2
Outlying district	Jinghai	501.16 -69.80	2.0	533.13	1000	2000	2
	Ninghe	317.93-44.28	1.3	305.08	550	550	1
	Wuqing	957.05-133.29	4.7	731.45	675	1350	2
	Baodi	422.15-58.80	2.5	478.15	1400	1400	1
	Jizhou	287.46-40.94	1.1	500.97	936	936	1
Binhai NewArea	Binhai	7,303.03-1,017.03	4.6	910.23	662	3310	5
	Total	16737.30-2331.10	4.30	1139.90	905	51583	57

*Chinese yuan and the corresponding amount in United States dollars given in billions; GDP, gross domestic product.

each in Jinghai and Baodi districts (Figure 5). Following the addition of these new hospitals, the service coverage area would expand significantly, with the population coverage increasing to 95.1%, reflecting 21.7% growth, as shown in Figure 6. This strategic placement can help address the existing gaps in healthcare service coverage to some extent, reducing the proportion of non-accessible areas.

Discussion

The results presented reveal a pronounced spatial disparity between the city's economic core, exhibiting a stark mismatch between development status and healthcare infrastructure availability. These spatial disparities are not incidental but reflect entrenched patterns of uneven urban development and resource

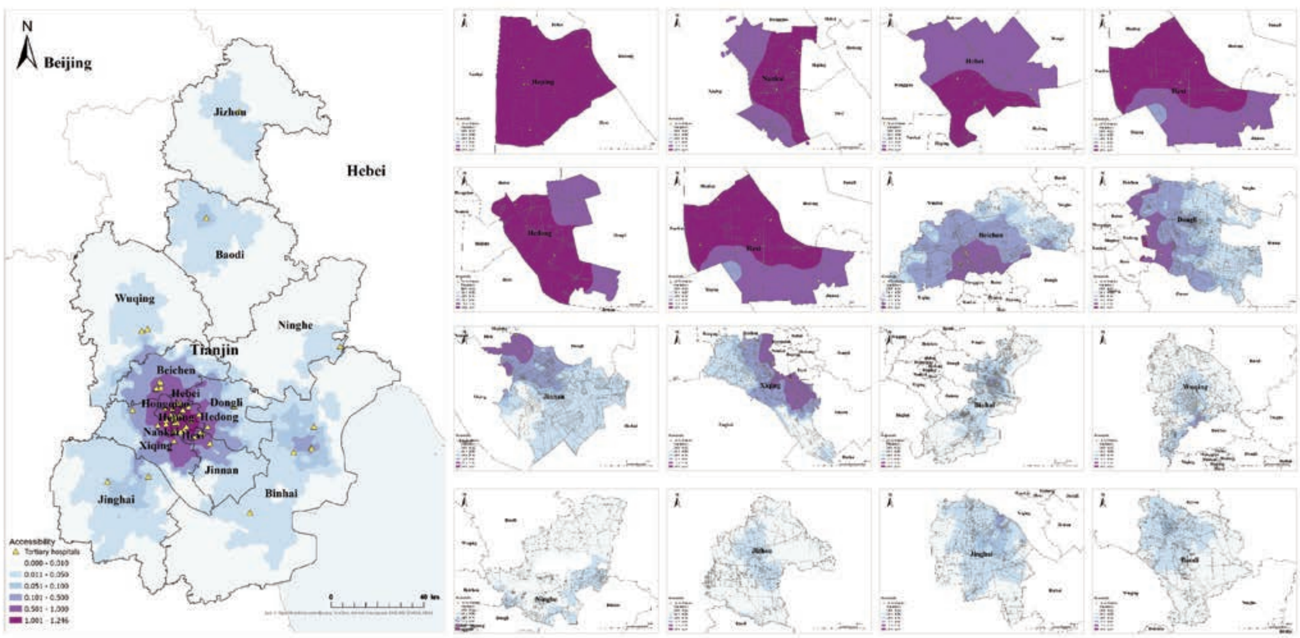

Figure 3. Geographic accessibility of tertiary hospitals in Tianjin and its administrative districts.

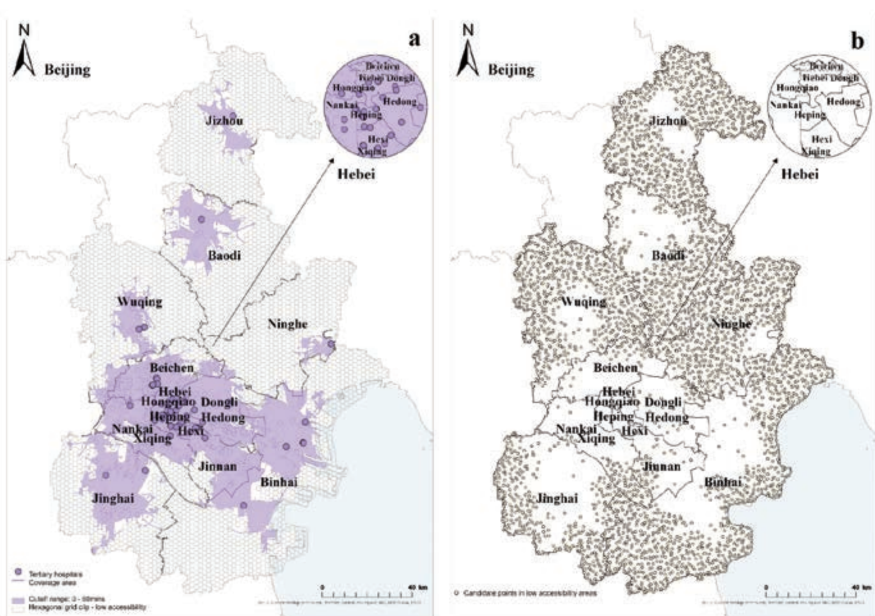

Figure 4. Service area analysis and candidate site identification for new tertiary hospitals in Tianjin.

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concentration. Optimizing the spatial allocation of newly planned tertiary hospitals in suburban and outer suburban districts is critical to ensuring equitable healthcare access across the city.

The centralization of advanced healthcare resources aligns with the theory of cumulative causation (Myrdal, 1957), wherein core areas continuously attract higher-level infrastructure and talent, creating self-reinforcing disparities over time. Similar spatial inequalities have been observed in other high-density metropolitan regions. For instance, in Paris, access to specialist cardiovascular procedures such as revascularization is significantly lower in non-central administrative areas where lower-income populations live (Gusmano *et al.*, 2014). In Seoul, tertiary hospitals remain clustered around traditional urban cores, despite the expansion of residential zones to suburban fringes (Lee *et al.*, 2025). These patterns illustrate a common challenge in urban health systems, namely the infrastructure justice gap between central and peripheral regions (Martínez, 2021; Isnan *et al.*, 2025). However, China's context introduces additional complexity. Highly centralized planning

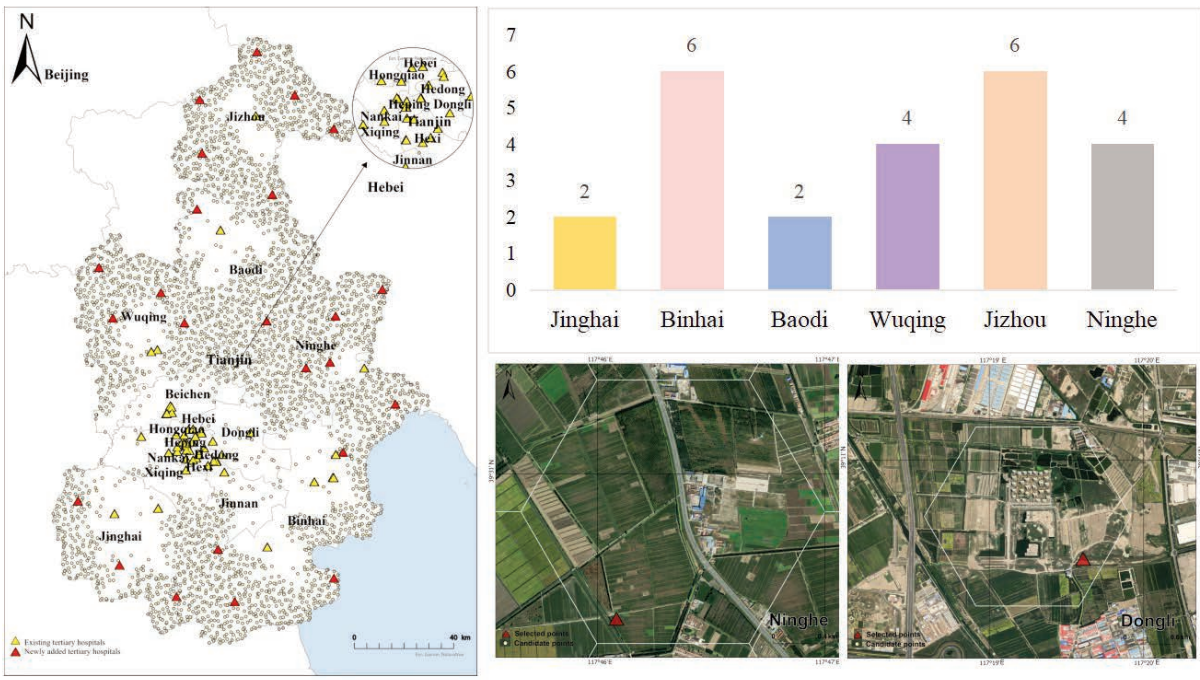

Figure 5. Optimal spatial allocation of new tertiary hospitals across Tianjin's administrative districts.

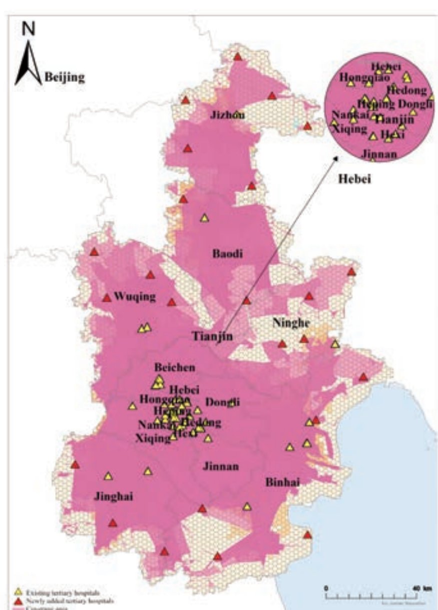

Figure 6. Service area analysis and candidate site identification for new tertiary hospitals in Tianjin.

mechanisms, rigid health financing structures and 'siloed' inter-agency coordination make responsive redistribution more difficult. This is particularly evident in Binhai New Area, where the region's critical economic role contrasts with a severe under-provision of advanced medical services. Such misalignments weaken health system resilience and threaten the long-term viability of urban development.

In response to the spatial disparities identified, this study applied a location-allocation model to optimize the layout of 24 planned tertiary hospitals, prioritizing areas with low accessibility and high population density. The optimized configuration significantly improved service coverage in suburban and outer suburban districts, particularly in underserved zones. While the redistribution results were promising, such spatial solutions alone cannot fully resolve systemic healthcare inequities. As existing literature suggests, optimization models are often constrained by static assumptions and limited flexibility in real-world implementation (Crown *et al.*, 2018). Factors such as inter-agency fragmentation, healthcare financing rigidity, and human resource shortages frequently hinder the actual deployment of newly planned facilities (Bayat *et al.*, 2023). Therefore, bridging the gap between spatial optimization and equitable healthcare delivery requires aligning infrastructure layout with functional reforms across different urban zones. The following recommendations address the distinct challenges faced by central districts, peripheral regions, and Binhai New Area.

First, to alleviate the overreliance on central tertiary hospitals and enhance system-wide efficiency, it is essential to accelerate the implementation of a functional referral system within a hierarchical healthcare framework. Instead of allowing high-level facilities to absorb all levels of demand, tiered service allocation should guide routine and chronic care to primary and secondary providers. This redistribution can reduce congestion, improve service quality, and ensure more appropriate use of advanced medical resources (Shen *et al.*, 2020; Zhou *et al.*, 2021; Yu *et al.*, 2024). Additionally, integrating telemedicine technologies can help create a collaborative network that optimizes resource allocation. Specific measures include financial incentives for specialists in central tertiary hospitals to deliver remote consultations, and deploying telemedicine terminals in underserved areas to strengthen regional healthcare connectivity (Grigsby, 1998; Weinstein *et al.*, 2014; Biancone *et al.*, 2023).

Second, for suburban and outer suburban regions with historically limited medical investment, expanding physical infrastructure must be accompanied by efforts to strengthen service delivery capacity. This includes offering incentives to retain qualified health professionals, enhancing the management capabilities of newly built facilities, and promoting professional exchanges across districts (Weiss *et al.*, 2018).In addition, closer coordination between transportation planning and healthcare services should be prioritized to improve accessibility for remote populations. Strategies such as dedicated bus routes to tertiary hospitals and emergency transfer systems for critical cases have proven effective in connecting isolated communities to advanced care (Chen *et al.*, 2023). These measures would not only improve spatial coverage but also support the long-term integration of peripheral areas into the broader metropolitan health network.

Third, Binhai New Area's disconnect between its economic importance and insufficient healthcare capacity signals a missed opportunity for regional health system strengthening. Rather than simply increasing facility numbers, policymakers should reposition Binhai as a regional healthcare hub by fostering integrated medical-industrial clusters, promoting partnerships between hospitals, research institutions, and biotech enterprises. Establishing cross-district referral mechanisms and digital health infrastructure can further enable Binhai to function as a coordination centre within Tianjin's broader healthcare network, supporting balanced growth and institutional resilience. This study has several limitations. First, due to the limited resolution and incomplete coverage of the Area Of Interest (AOI) data, a hexagonal grid system based on total population per grid was used, which may overlook fine-grained population distribution. Second, several practical constraints may hinder the implementation of the optimized facility layout, including fragmented institutional coordination, rigid health financing mechanisms, and shortages of qualified healthcare personnel. Third, although the findings provide valuable insights into spatial disparities in Tianjin, their generalizability to other urban contexts may be limited. Cities with differing demographic structures, institutional arrangements, or healthcare systems may require contextual adjustments when applying similar optimization strategies. Finally, data-related limitations remain, particularly the use of hospital bed counts and healthcare staff numbers as proxies for service capacity, which may not adequately capture differences in care quality or patient preferences. Future research should explore the following directions. First, Geographic Information Systems (GIS) and high-resolution remote sensing imagery, combined with urban building data, could be utilized to obtain precise population data at specific residential locations, replacing hexagonal grid population totals as the demand indicator. Second, incorporating healthcare service quality and patient behavior preferences into the optimization model would provide a more comprehensive perspective for evaluating the level of resource supply. Finally, conducting long-term evaluations of newly established tertiary hospitals, integrated with dynamic optimization models, could simulate evolving demand patterns and assess the effects of policies over different time periods.

Conclusions

The evaluation of the spatial accessibility of tertiary hospitals in Tianjin using a 1-hour travel time threshold found significant disparities between central and peripheral districts as the tertiary hospitals are predominantly concentrated in central areas. Overall, less than a third of the city's area, with close to three quarters of its population, fell within the service range of existing tertiary hospitals, underscoring the severe spatial imbalance in advanced medical resource allocation. To address the gaps revealed, 24 new tertiary hospitals would be needed, prioritizing areas with low accessibility and high population density. This would significantly improve service coverage in underserved regions, substantially reduce the proportion of non-accessible points in peripheral districts and better align medical resources with regional development needs.

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Online supplementary materials

Appendix A

Figure A1. Geographic accessibility of tertiary hospitals in Tianjin and its administrative districts based on healthcare staff numbers.