Title Evaluating the Spatial Equity of Urban Educational Resources Against the Backdrop of Population Change: A Case Study of Urumqi' s Main Urban District

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Abstract

By collecting data from the national population census, locations of primary schools and residential areas in Urumqi in 2020, urban road networks, and other relevant sources, this study employs methods such as numerical statistics, buffer analysis, and cost matrix analysis to conduct an in-depth investigation into the spatial equilibrium of primary school educational resources in Urumqi. The research indicates: (1) Currently, the distribution of primary school educational resources in Urumqi is uneven, with Tianshan District and Saybag District being relatively more abundant, while some areas in Xinshi District, Toutunhe District, and Shuimogou District are relatively insufficient. (2) Primary schools within a 0–4 minute driving time accessibility range in Tianshan District, Saybag District, and Xinshi District could become candidate schools for educational resource output or optimization adjustment in the future. (3) Influenced by changes in the school-age population structure, educational resources in Urumqi may once again experience a supply exceeding demand by 2026, providing objectively favorable conditions for improving the imbalance of urban educational resources. (4) Primary school educational resources are relatively scarce in high nighttime light index areas within some subdistricts of Xinshi District, Shuimogou District, Saybag District, and Toutunhe District, and these areas are recommended for focused attention in the future. The findings of this study can provide scientific references for the spatial adjustment of educational resources in Urumqi in the future.

Full Text

Assessing the Spatial Equity of Urban Educational Resources Under the Background of Population Changes: A Case Study of the Main Urban Area of Urumqi City

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Abstract

By collecting data from national population censuses, the locations of primary schools and residential areas in Urumqi City in 2020, urban road networks, and other relevant data, this paper employs numerical statistics, buffer zone analysis, cost matrix analysis, and other methods to conduct an in-depth investigation into the spatial equity of primary education resources in Urumqi City. The study findings are as follows: (1) The current distribution of primary education resources in Urumqi City is uneven, with relatively greater abundance in the Tianshan and Shayibake Districts, while parts of the Xinshi, Toutunhe, and Shuimogou Districts face relative scarcity. (2) Primary schools within a 0-4 minute driving range in the Tianshan, Shayibake, and Xinshi Districts may serve as candidate schools for exporting or optimizing primary education resources in the future. (3) Affected by changes in the structure of the school-age population, Urumqi' s education resources may again experience supply exceeding demand by 2026, providing objectively favorable conditions for improving the imbalance of urban education resources. (4) Some streets in the Xinshi, Shuimogou, Shayibake, and Toutunhe Districts with high light index values have relatively scarce primary education resources, warranting focused attention in the future. These research results can provide scientific references for future spatial adjustments of educational resources in Urumqi City.

Keywords: population trends; educational resource optimization; accessibility analysis; school-age population; Urumqi City

1 Study Area Overview

Urumqi City is located in the hinterland of the Eurasian continent, situated on the northern slope of the Tianshan Mountains and adjacent to the southern margin of the Junggar Basin, with geographical coordinates between 86°46$ '10' ' 88°59' 48' ' $E. As the capital of Xinjiang Uygur Autonomous Region, Urumqi serves as the political, economic, information, and cultural center of the entire region, as well as an international transportation hub and gateway to opening up in western China. Urumqi currently governs 7 districts and 1 county, including Tianshan District, Shayibake District, Xinshi District, Shuimogou Dis-

trict, Toutunhe District, Midong District, Dabancheng District, and Urumqi County. Since the administrative boundaries of Midong District, Dabancheng District, and Urumqi County changed after 2007, resulting in inconsistent statistical calibers across population censuses, this study selects five urban districts —Tianshan, Shayibake, Xinshi, Shuimogou, and Toutunhe—as the research area to ensure data comparability. The school-age population in Urumqi has shown a declining trend since 2010. Since the implementation of the two-child policy in 2016, the decline rate of the primary school-age population has been somewhat mitigated, but the overall downward trend has not reversed. According to the 2022 Statistical Bulletin of National Economic and Social Development of Urumqi City[11], the total number of students enrolled in compulsory primary education in the city was 264,000, with 44,000 new primary school enrollments, a decrease of 4,000 compared to 2021.

2 Data and Methods

2.1 Open-source Geographic Data

This study employs web crawler technology to obtain spatial element data for primary schools, residential areas, and urban road networks in the five urban districts of Urumqi City in 2020 from the Amap Open Data Platform (Fig. 1). A total of 15,000 roads at various levels in Urumqi were collected. By considering vehicle speed limits and road lengths, travel times (under smooth traffic conditions) were calculated to generate the urban transportation road network dataset for Urumqi.

2.2 Population Data

The national population census is a social statistical activity that systematically collects and records basic population information, typically conducted every 10 years, documenting national population size, structure, distribution, and living conditions. The total population and age structure data for the five urban districts of Urumqi used in this study are derived from the fifth (2000), sixth (2010), and seventh (2020) national population census data[12].

2.3 Population Density and Urban Nighttime Light Data

Population density data are raster data that distribute population data from administrative units onto spatial grids through a multi-factor weight allocation method incorporating residential density, land use type, and nighttime light brightness, effectively addressing the issue of insufficient spatial precision in population statistics. Urban nighttime light data utilize low-intensity illumination information emitted by urban nighttime lights, residential areas, and traffic flows, reflecting the scope of human activity and urbanization degree. The 2020 Urumqi population density and urban nighttime light datasets used in this paper are derived from research results by Xu Xinliang' s team at the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of

Sciences[13,14]. These data are based on the WGS1984 geographic coordinate system, with spatial resolutions of 0.008° (approximately 0.5 km) and 0.004° (approximately 0.5 km), respectively. Based on this foundation, the natural breaks classification method is used to grade the data, with subsequent processing including map sheet clipping, spatial analysis, and mapping.

2.4 Buffer Zone Analysis

Buffer zone analysis is a method that establishes buffer zones of specified widths around geometric objects[15]. It can be defined as: $B = \{x \mid d(x, A) \leq R\}$, where B represents the buffer zone; d is the set of points; x is a point within the buffer zone; A is the object; and R is the neighborhood radius (buffer radius). A buffer zone with radius R comprises all points within a region less than radius R from center A. According to the Standard for Design of Primary and Secondary Schools (GB 50099-2011), the service radii for urban primary schools and junior high schools are 500 m and 1000 m, respectively. This study establishes multi-ring buffers of 500 m, 1000 m, and 2000 m for primary schools in Urumqi to assess the spatial characteristics of primary school distribution and existing service capacity.

2.5 Cost Matrix Analysis

Cost matrix analysis is a method for calculating the lowest-cost paths between multiple origins and multiple destinations in a network[16]. Compared with shortest path analysis, it is more suitable for solving distance analysis problems involving large numbers of points. This method first calculates the network impedance from each origin to all destinations, then determines the lowest-cost network paths from multiple origins to multiple destinations. Based on Urumqi' s road network distribution and road travel speeds, this study constructs an OD cost matrix to calculate the time costs from all residential areas in Urumqi to their nearest five primary schools, and employs Inverse Distance Weighting (IDW) interpolation to generate a comprehensive primary education service accessibility map for the urban area of Urumqi.

3 Results

3.1 Analysis of Primary School Service Capacity in Urumqi Districts

According to POI data for primary schools and residential areas in Urumqi, the city currently has 143 primary schools and 3,104 residential areas. Among these, Shayibake District, Tianshan District, and Xinshi District have relatively large numbers of primary schools, while Xinshi, Shayibake, Tianshan, and Shuimogou Districts have relatively large numbers of residential areas.

Based on buffer zone analysis methods, this study establishes multi-ring buffers for Urumqi' s primary schools with radii of 500 m, 1000 m, and 2000 m. By examining the buffer service coverage of primary schools and the number of res-

idential areas they encompass (Table 2), we can preliminarily assess the service capacity of primary schools for residential areas across districts. The results indicate that 39.79% of the city' s residential areas fall within the 500 m service range of primary schools, 31.61% are within the 500-1000 m range, 19.28% are within the 1000-2000 m range, and another 9.32% are located beyond the 2000 m range. Specifically, Tianshan and Shayibake Districts have relatively richer or denser primary education resources, with higher proportions of their residential areas within the 500 m range of primary schools at 61.61% and 46.84%, respectively. Xinshi District has a slightly lower density of primary education resources, with a higher proportion (36.99%) of its residential areas falling within the 500-1000 m range. Toutunhe District exhibits the lowest density of primary education resources, with 22.12% of its residential areas within the 500 m range and 43.75% located beyond 2000 m. Additionally, 29.23% and 20.98% of residential areas in Xinshi and Shuimogou Districts, respectively, fall within the 1000-2000 m service range. These results reflect that some residential areas in Toutunhe, Xinshi, and Shuimogou Districts are relatively far from schools, warranting focused attention in future educational resource optimization.

3.2 Accessibility Analysis of Primary Education Services in Urumqi

Using the urban road network and OD cost matrix methods, we can analyze the accessibility from each primary school to each residential area in Urumqi and identify which primary schools have surplus educational resources available for optimization. This study collected a total of 15,000 roads at various levels in Urumqi. By considering vehicle speed limits and road lengths, travel times (under smooth traffic conditions) were calculated to generate the urban transportation road network dataset for Urumqi. Ultimately, the actual time required from all residential areas in Urumqi to their nearest five primary schools —that is, driving time without traffic congestion—was calculated, and interpolation was applied to generate an accessibility map of primary education services from each residential area to the nearest primary school (Fig. 2).

Considering the distribution of primary schools across districts, those within a 0-4 minute driving accessibility range are mainly located in Tianshan, Shayibake, and Xinshi Districts (Table 3), with 19, 15, and 11 primary schools, respectively. These schools are mostly situated in areas with relatively surplus educational resources and can serve as candidate schools for exporting or adjusting primary education resources in Urumqi in the future.

3.3 Analysis of Primary School-Age Population Structure Changes in Urumqi

According to data from successive population censuses, the population structure composition of various districts in Urumqi exhibits different characteristics (Fig. 3). Based on the age classification standards of population census data, this study employs the population numbers of 5-9 year-olds (2020 current student age group), 0-4 year-olds (2020 birth population), and 10-14 year-olds (2020

primary school graduation age group) to evaluate the structural changes in school-age populations across districts.

The comprehensive data on children across different age groups in all districts show the characteristic pattern of 0-4 year-old population < 5-9 year-old population < 10-14 year-old population, indicating that the number of students in the graduation age group exceeds that in the current student age group. Consequently, the population demand for primary schools in 2020 across districts exceeded the service capacity of previous primary education resources. However, examining the trends in 0-4 year-old population (children already enrolled or about to enroll) and birth population reveals that only Tianshan District shows a declining trend, suggesting that the school-age population in Tianshan District may decrease. Its relatively abundant educational resources could be optimized and reallocated to areas with relative resource scarcity such as Xinshi and Toutunhe Districts. This provides objectively favorable conditions for addressing urban education resource imbalances and should attract the attention of education management departments.

3.4 Spatial Coupling Between Education Resources and Population Distribution in Urumqi

Based on Urumqi' s population density map (Fig. 4) and urban nighttime light distribution map (Fig. 5), the population density across the five urban districts of Urumqi ranges from 0.0 to 1.1$×$10^-2, while the urban light index ranges from 0.31 to 149.39. Comparing the distribution characteristics of population density and urban nighttime lights in Urumqi reveals good similarity between the two in the city' s core areas. However, population density data lack precision in districts such as Xinshi, Shuimogou, and Toutunhe. In contrast, urban nighttime light data cover larger built-up areas and better reflect urban development and population distribution characteristics.

Using the natural breaks classification method to divide Urumqi' s population density and urban light index into five levels allows us to grasp the spatial extents of high, relatively high, medium, relatively low, and low levels of population density and urban nighttime lights. Overlaying primary school locations with the classified population density and urban light index data enables evaluation of the coupling between primary education resources and population density/urban development intensity across various streets in Urumqi (Table 4). Statistical results from the population density classification map show that Urumqi' s primary schools are mainly distributed in high and relatively high population density areas of Tianshan and Shayibake Districts, medium and relatively low density areas of Xinshi District, and low density areas of Shuimogou and Toutunhe Districts. In contrast, classification statistics based on urban nighttime lights indicate that primary schools are mainly distributed in high and relatively high light index areas across all districts. The light index statistics better reflect the actual distribution of primary schools across Urumqi' s districts.

Comprehensive analysis of the above maps and data reveals that streets with good spatial coupling between high light index areas and primary school distribution include: Jiefang North-South Road in Tianshan District, Youhao Road and Changjiang Road in Shayibake District, Qidaowan in Shuimogou District, and Yingbin Road in Xinshi District. Simultaneously, some high light index areas with relatively few primary schools are identified, mainly including: Ergong, Changchun Middle Road, and Bajiahu Streets in Xinshi District; Longsheng Street and Qidaowan Street in Shuimogou District; the High-Speed Rail Area in Shayibake District; and the Bainiaohu Area in Toutunhe District. These areas contain numerous newly constructed residential buildings and may require prioritized increases in primary education resource supply in the future.

4 Discussion

Similar to other domestic research findings[6,7], this study reveals that Urumqi also exhibits characteristics of relatively abundant educational resources in central urban areas and relative scarcity in peripheral or newly developed urban areas. This paper employs buffer zone analysis and OD cost matrix methods to conduct in-depth investigations from two perspectives: the satisfaction of primary school service demand for residential areas across districts, and the surplus degree of educational resource accessibility.

From an administrative division perspective, primary education resources in Tianshan and Shayibake Districts are relatively concentrated and densely distributed, enabling residents in these urban areas to enjoy high rates of nearby school enrollment, particularly in Tianshan District. In contrast, some residential areas in Toutunhe, Xinshi, and Shuimogou Districts are far from primary schools, highlighting spatial imbalances in educational resource layout. This study provides a list of primary schools within a 0-4 minute driving accessibility range, most of which are located in areas with relatively surplus educational resources and can serve as candidate schools for exporting or adjusting primary education resources in Urumqi in the future.

According to primary education service accessibility analysis results, primary schools within a 0-4 minute driving accessibility range are mainly distributed in Tianshan, Shayibake, and Xinshi Districts, with 19, 15, and 11 primary schools, respectively. These schools have relatively surplus educational resources and can become candidate schools for exporting or adjusting primary education resources in Urumqi in the future.

Through analysis of children across different age groups, we can anticipate that under the influence of the universal two-child policy, 2022 will witness a brief peak in primary school-age children, with numbers gradually declining after 2026. Particularly, Tianshan District may experience a decrease in school-age children, implying that educational resources in this district may become further surplus, providing an opportunity for optimizing resource allocation and alleviating shortages in other areas.

The spatial coupling relationship between educational resources and urban nighttime light index reveals that some high light index areas have relatively few primary schools, mainly including: Ergong, Changchun Middle Road, and Bajiahu Streets in Xinshi District; Longsheng Street and Qidaowan Street in Shuimogou District; the High-Speed Rail Area in Shayibake District; and the Bainiaohu Area in Toutunhe District. We recommend that future optimization of educational resource layout in Urumqi focus on these streets and areas.

Comparing Urumqi' s population density and urban nighttime light distribution characteristics reveals good similarity between the two in the city' s core areas. Relatively speaking, urban nighttime light distribution data cover larger built-up areas with higher spatial resolution, better reflecting urban development intensity and intra-district population characteristics. Results indicate that high and relatively high light level areas in Ergong, Changchun Middle Road, Bajiahu Streets of Xinshi District; Longsheng Street, Qidaowan Street of Shuimogou District; High-Speed Rail Area of Shayibake District; and Bainiaohu Area of Toutunhe District have relatively few primary schools. We recommend that future optimization of educational resource layout in Urumqi prioritize these streets and areas.

This study also has certain limitations. For instance, the spatial data for primary schools and residential areas used in this paper are from 2020, while the supply and demand situation for educational resources in Urumqi may change between 2020-2026. Additionally, due to limitations in the collected educational resource data, other factors affecting educational resource equity such as class size capacity, school teaching quality, and teacher-student ratios were not considered. In future research, we could consider expanding the research scope and collecting more comprehensive data to provide more thorough recommendations for optimizing primary education resources in Urumqi.

5 Conclusion

(1) Primary education resources in Urumqi' s Tianshan and Shayibake Districts are relatively richer or more densely distributed. However, some residential areas in Xinshi, Toutunhe, and Shuimogou Districts are relatively far from schools, requiring focused attention in future educational resource optimization.

(2) According to primary education service accessibility analysis results, primary schools within a 0-4 minute driving accessibility range are mainly distributed in Tianshan, Shayibake, and Xinshi Districts, with 19, 15, and 11 primary schools, respectively. These schools have relatively surplus educational resources and can serve as candidate schools for exporting or adjusting primary education resources in Urumqi in the future.

(3) After experiencing a brief period of supply falling short of demand around 2022, Urumqi's primary education resources may again face supply exceeding demand by 2026. The reduction in school-age population in Tianshan

District, which has superior educational resources, will be greater than in areas with weaker resources such as Xinshi and Toutunhe Districts. This provides objectively favorable conditions for improving urban education resource imbalances.

(4) The spatial coupling relationship between educational resources and urban nighttime light index indicates that some high light index areas have relatively few primary schools. We recommend that future educational resource layout optimization in Urumqi prioritize Ergong, Changchun Middle Road, and Bajiahu Streets in Xinshi District; Longsheng Street and Qidaowan Street in Shuimogou District; the High-Speed Rail Area in Shayibake District; and the Bainiaohu Area in Toutunhe District.

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Note: Figure translations are in progress. See original paper for figures.