Primary Medical Centers Allocation – A Case Study in Southeast Guizhou, China

MUSA 6950 Final Project

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Abstract

This paper investigates the optimization of healthcare resource distribution in Southeastern Guizhou Province, China, using a capacitated P-median model. This region is characterized by medical resource insufficiency and demographic disparities, which has prompted the need for strategic planning of healthcare infrastructures. The study aims to optimally locate 120 county-level Grade A primary medical centers based on factors such as population density, healthcare facility distribution, and road networks. Using ArcGIS Pro for spatial analysis, the model addresses challenges such as the limited capacities of health centers and the cost of travel, especially the distance of traveling from residential areas to their nearest medical center. Additionally, this paper suggests that the rugged terrain, affordable budget, and Environmental Impact Assessments (EIA) should be integrated into future assessments and implications. The results of this study are intended to guide local policy decisions, improving healthcare accessibility and infrastructure in rural areas of Southeastern Guizhou Province.

I. Introduction

Medical insufficiency and imbalance have been an intractable problem since the founding of the People's Republic of China in 1949. With the rapid increase of population and urban development, the demand for basic medical resources is also expanding. However, according to Zhang (2023), hospitals with advanced technology and equipment and registered professional doctors are more concentrated in the capital city of each province or with the reputation of the affiliated medical colleges. When comparing China to Switzerland and Austria, where the ratio of doctors per 1000 people is 4.4, China's ratio stands at 2.5. Additionally, among the registered doctors, only 17% hold a Master's degree, while half of them possess a Bachelor's degree, indicating a disparity in the level of expertise. Another essential index in analyzing medical resources is bed ratio. In China Statistics Yearbook (2023), by the end of 2022, there were 9.75 million beds in medical and health institutions nationwide, with 6.92 beds per 1000 per capita. However, the statistics cannot reflect the truth in the real world. The problem of shortage of beds still exists, especially during the flu season. There are three main reasons: the lack of trust in the community healthcare center, the limitation of rehabilitation services in the healthcare chain, as well as the restriction of insurance medical payment. Therefore, distributing the population in adjacent counties and towns to the nearest primary medical facilities and enhancing their medical infrastructure is an efficient method to mitigate the pressure of the general hospitals.

The case study area for this paper is the Southeastern Guizhou Prefecture, which is located in the mountainous area of Southwestern China (Figure 1.1). The distribution of medical facilities in China shows a significant gap between the eastern and western regions. When examining the concentration of healthcare resources, the mean values in Western Regions are much lower compared to other areas. Since the influence of economic growth on the concentration of healthcare resources is both significant and positive, the GDP per capita in Guizhou is below $50,000 and is less than the national average. Educational resources, specifically the number of colleges and prospective students prepared to work in hospitals, are also lacking (Guo & Luo, 2019).

Furthermore, in southwestern China, the distance to the nearest primary healthcare centers is longer than in other parts, with Guizhou averaging more than 10 kilometers from the nearest healthcare centers (Jia et al, 2022). The current situation is that general hospitals managed by provinces and cities are overloaded, while county-level primary healthcare centers much closer to rural residential areas often lack the technologies and doctors to deal with complicated health issues. Therefore, even though there might be a closer primary medical facility nearby, people still travel longer to general hospitals. Based on the national medical institution setting plan for 2025, Grade A County primary healthcare centers should offer at least 100 beds, and the goal for 2025 is to provide 3.5 beds per 1000 per capita. According to the current data from Gaode Map, there are 225 county-level primary healthcare centers in Southeastern Guizhou Prefecture, but few of them are in Grade A. The recent Census data shows that the total population in Southeastern Guizhou Prefecture is 3.4 million, indicating at least 119 Grade A primary healthcare centers. Therefore, we might need to consider which existing primary healthcare centers should keep their locations to upgrade, close, or re-allocate. To solve the problem, we designed a capacitated P-median model to optimize the locations of primary healthcare centers, which provides advice for the local policymakers to achieve the government's goal for 2025.

Figure 1.1 Map of Qiandongnan with its relative location in China.

II. Literature Review

Optimization models have been widely used in policy-making for improving public amenities, including education, transportation, and medical services. Their general goal is to create equal and convenient opportunities for the residents in this area. While the optimized locations of public amenities should cover the largest service areas with less time costs, the restricted budget in relocating or opening new locations is inevitable. Delmelle et.al (2014) conducted research of allocating school locations in Charlotte, NC, to reduce students' road costs with a Vintage Flexible Capacitated Location Problem (VFCLP) (p. 267). The bi-objective functions of the model not only consider minimizing the traffic costs and the exponential additional costs for students who are not within the buffer distance but also attempt to minimize the expenditures of opening, relocating, or demolishing a school and adding mobile classrooms (p. 269), which provides comprehensive information of the tradeoffs and its potential influence in arranging school closures in the recent future.

Unlike the school-allocation problem that the facility locations are fixed, Hashemi, et.al (2022)'s research of optimizing emergency medical service considers random customers' distribution and congestion-prone mobile facilities so that the ambulance would continue serving the next customer rather than returning to its base (p. 4). Its objective function aims to maximize demand coverage in the study area and minimize penalties from relocating ambulances between emergency medical service centers over different periods with the consideration of coverage quality. Utilizing contour lines for modeling and a genetic algorithm for problem-solving because of the NP-hard nature of the model, their research significantly enhances the speed and efficiency of EMS responses (pp. 7-10). In our research, since it does not involve emergency medical services, such a dynamic facility optimization solution might not be applicable.

Flores et al. (2021) address the optimization of health facility location to enhance universal health care in the Philippines, a developing country with low and middle income, focusing on the deployment of primary care facilities. The study utilizes the Cooperative Covering Maximal model, a variation of the Location Set Covering Model that attracts patients based on distance among multiple available facilities to suggest optimal locations for these facilities based on access equity and operational efficiency (p. 2). The geographic characteristics of the study area they chose are similar to those in our study, in which both of them are mountainous with large rural areas. In addition, the criteria they set are based on the Philippine Health Facility

Development Plan, giving the accurate goal of developing the model results (p. 4). To compare the model results, they conducted four different methods with a detailed demonstration of the advantages and shortcomings of each method (p. 8). The model presents locations that maximize service to the populace while considering geographic and infrastructure constraints, offering a significant step towards evidence-based health facility planning. The research gives a comprehensive understanding of how to choose compatible models for each study area. For our research, based on the medical insurance for the fixed healthcare facility rule in China that medical institutions voluntarily sign medical insurance service agreements with regional medical insurance agencies to provide medical and drug services for insured personnel, we choose capacitated P-median model to allocate residents in Southeast Guizhou rural area to their nearest medical facility.

III. Methods

1. Data

The data we use in the capacitated P-median model includes the boundary of Southeastern Guizhou, the population in county level, residential areas as demand nodes, current existing primary healthcare centers as facilities, and the road network. The geographic boundary and population are retrieved from National Geographic Information Data Center and 2020 7th Census Data, while the residential area and road networks with all classes are downloaded from OpenStreetMap (OSM) in Python. Since there is no specific population based on each residential area, we calculate it through the proportion between each residential area and the total residential area in this county. The facilities are retrieved from Gaode Map, an online map platform widely used in China, and we selected the type "county-level primary medical center" as our targets. In total, there are 1741 residential areas and 171 medical centers. Figure 3.1 is a data preview for the current distributions of facilities and demands. Most of the residential areas are concentrated in the west, surrounding Kaili City, while there are few in the center. The primary health care centers are distributed more evenly, but some of them are hard to access by identified roads.

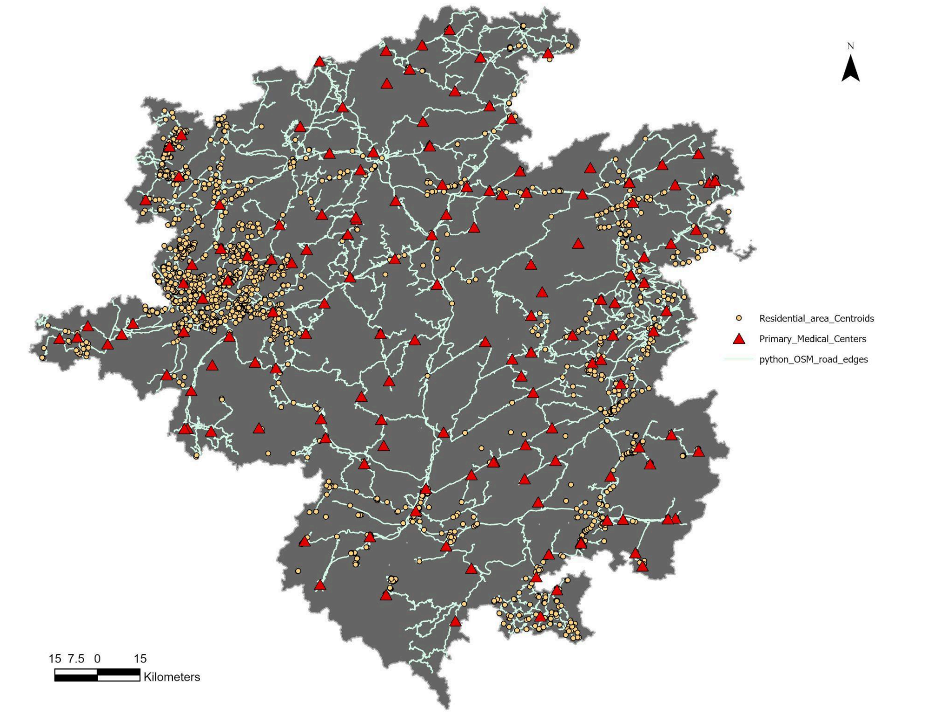

Figure 3.1 Data Preview

2. Model Formulation

The objective function of the capacitated P-median model is constructed as below:

$$Min \sum_{i=1}^{I} \sum_{j=1}^{J} a_i d_{ij} x_{ij} \qquad (1)$$

Subject to:

$$\sum_{j \in J} x_{ij} = 1 \; \forall i \qquad (2)$$

$$x_{ij} \le y_j \; \forall i, \; \forall j \qquad (3)$$

$$\sum_{j \in J} y_j \le P \qquad (4)$$

$$\sum_{i \in I} a_i x_{ij} \le Z_j^{+} \, y_j \; \forall j \qquad (5)$$

$$x_{ij} \in \{0, 1\} \qquad (6)$$

$$y_j \in \{0, 1\} \qquad (7)$$

Where $x_{ij} = if\ \ demand\ f\,rom\ residential\ area\ i\ is\ assigned\ to\ medical\ center\ j$

$y_{j\,=}\ if\ \ a\ medical\ center\ is\ established\ at\ location\ j$

$d_{ij} = Distance\ between\ residential\ area\ i\ and\ medical\ center\ j$

$a_i = demand\ in\ residential\ area\ i$

$$= \left(\frac{Pop_i}{1000}\right) \cdot 3.5$$

$$where\ Pop_i = County_m Pop \cdot \left(\frac{Area_i}{\sum_{Area\ i} County_m}\right)$$

$z_j^+ = 100\ (\ Total\ number\ of\ \ beds\ in\ medical\ center\ j)$

Eq. 1 defines the objective function that, limiting the capacity to 100 beds, where to locate 120 county-level Grade A primary medical centers and how to assign demand in each residential area to those medical centers to minimize the distance cost between them. Constraint (2) indicates that each demand node must be serviced by at most one facility. Constraint (3) restricts that a demand node is served by a facility only if the facility is actually opened and constraint (4) restricts the number of facilities that can be opened in the system should be less or equal than P. Constrain (5) regulates that the total demand should be less or equal than the maximum capacity of the facilities, and (6) and (7) defines the assigned demand and medical center as integers. Based on the calculation of the guidelines, we set 120 as a threshold that at least 120 facilities would satisfy the population demand in the study area.

3. Tools

The main tool we use to solve the capacitated P-median model is ArcGIS Pro. After inputting the road network and other data, we choose Location-Allocation Network Analysis and use the Maximize Capacitated Coverage. To make a better comparison, we run the model separately with the number of facilities equal to 1, 30, 60, 90, 120, and 150.

IV. Results

Our study utilized a Capacitated P-median model to identify optimal locations for 120 county-level Grade A primary medical centers in Qiandongnan Prefecture. This analysis was supported by comprehensive data sets including population density, current healthcare facility distributions, and road networks.

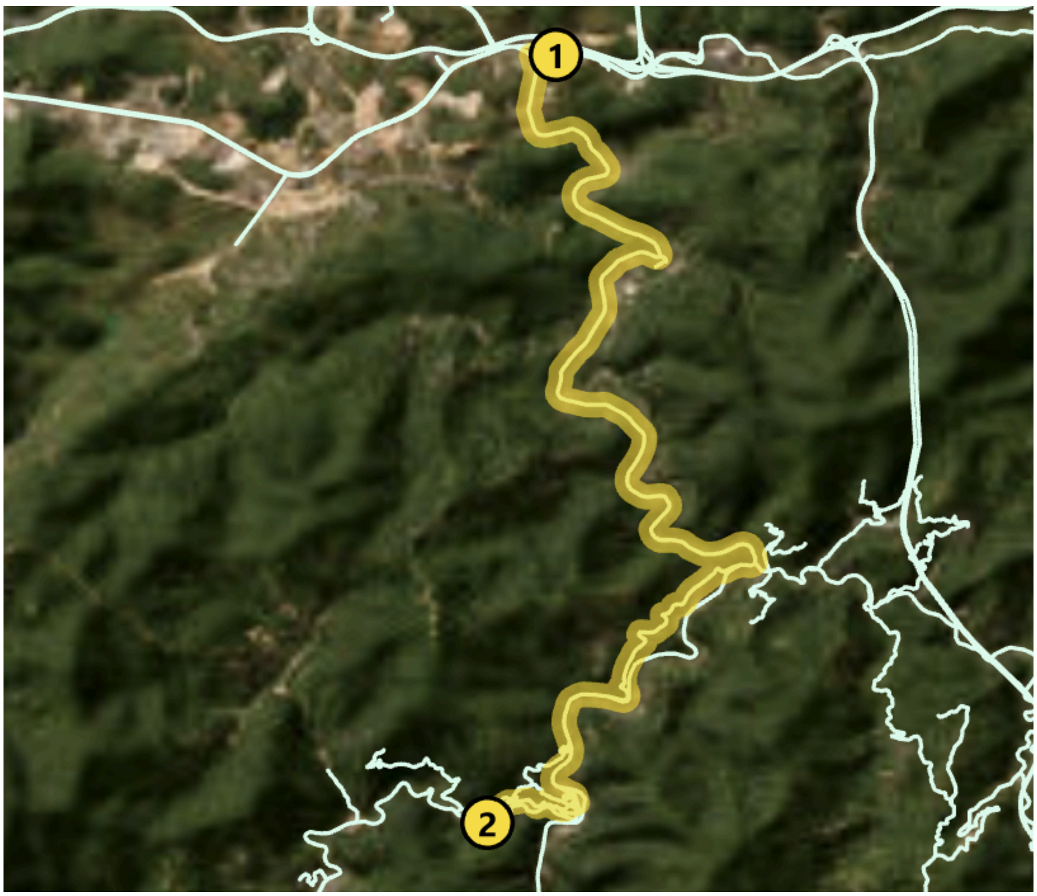

Figure 5.1 Example of road analysis from the centroid of a residential area to a primary medical center.

Our road network analysis, as illustrated in Figure 3.1, highlighted the paths connecting the centroid of a residential area (indicated by 1) to a primary health center (indicated by 2), which are crucial for determining the feasibility and efficiency of the location strategy. The road analysis identifies all primary health centers are accessible for residential areas via the shortest possible routes, which is critical for emergency cases where efficiency is of the essence. As demonstrated in the figure, due to the mountainous terrain where our study area is located, the route from a residential area to a primary health center is sinuous.

P=	1	30	60	90	120	150
# of Residential Area covered	10	370	1132	1870	2482	3161
Maximum Weighted Distance (km)	4.78	19.41	194.11	523.95	1041.21	2631.77
Average Weighted Distance (km)	1.98	11.44	12.90	12.56	22.45	36.09
Max Distance (km)	1.19	38.1	63.73	44.15	54.91	77.75
Avg Distance (km)	0.50	2.91	4.40	4.22	6.76	9.73

Table 5.1 Results of different numbers of primary health centers.

Table 5.1 presents detailed information on the impact of increasing the number of primary health centers on the accessibility of healthcare services to residential areas, using a range of distance metrics measured in kilometers. Each scenario provides insights into how well the healthcare needs of the population are met as the number of centers increases from 1 to 150.

The first column, labeled 'P', represents the number of primary health centers considered in each scenario. The subsequent column, '# of Residential Area Covered', demonstrates the total number of residential areas that have access to at least one primary health center under each scenario. With our goal of establishing 120 grade A primary health centers, 2482 residential areas can be covered by the service. As expected, this number will increase as more health centers are established, reflecting broader healthcare coverage across the study area.

The 'Maximum Weighted Distance (km)' metric represents the longest distance from the centroid of a residential area to a health center, weighted by population traveled. This distance increases significantly as the number of centers increases from 1 to 150, suggesting that the addition of primary health centers significantly increases the covering of the medical needs of residents. The 'Average Weighted Distance (km)' shows a general increase as more health centers are added, underlining the improved coverage of medical services as well.

The 'Max Distance (km)' and 'Average Distance (km)' show an initial increase in both maximum and average travel distances as more health centers are added but with a dip observed when the number of health centers reached 90 and 120. This pattern suggests that health center placements at these points offer optimal reach to the most distant residential areas, and indicate a more efficient distribution of medical centers that effectively improve accessibility.

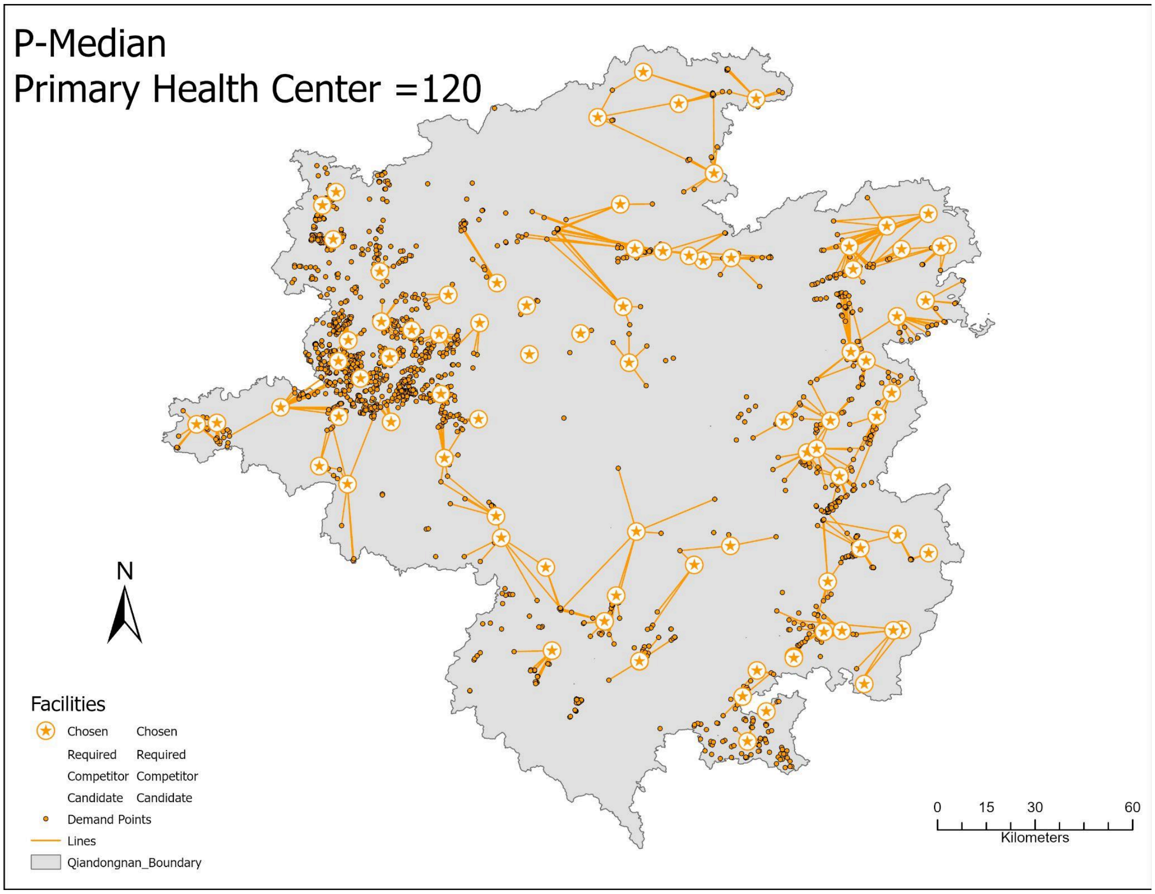

Figure 5.2 Map of distribution of the 120 primary medical centers.

The map shows the distribution of 120 primary health centers, indicated by the starred orange circles. These locations are the chosen facilities of a capacitated P-Median analysis aiming to minimize the overall travel distances with the most population covered. The orange lines connecting the chosen medical centers with demand points represent routes between the residential areas and primary medical centers.

The distribution of the health centers shown in the map follows the distribution pattern of residential areas. For denser populated areas such as the east and west regions of Qiandongnan County, more health centers are placed and the routes are significantly shorter. In the central region of Qiandongnan County where residential areas are sparse, fewer health centers and longer routes are connecting residential areas with the health centers. This distribution pattern of medical centers suggests a thorough consideration of both densely populated areas and more remote locations, balancing the goal of reducing travel time and distance while maintaining healthcare service delivery across the region.

VI. Discussion

The optimization of healthcare facility placement in Qiandongnan, while initially centered on minimizing distance and time costs across various transportation modes, also has the necessity to consider additional critical factors such as elevation and terrain, budget constraints for updating facilities, scenario analysis for model robustness, and environmental impacts. Each of these factors plays a vital role in ensuring the sustainability and effectiveness of healthcare delivery in this region.

Qiandongnan County is characterized by its rugged terrain and significant elevation variations, which can influence transportation times and cost more significantly than Euclidean distance. The current model focuses on optimizing the locations of primary healthcare centers based on Euclidean distance and time; however, incorporating elevation and terrain data could provide a more accurate representation of access times and resource allocation. Roads winding through mountainous areas will increase travel time disproportionately, even if the distances are short. Enhanced GIS modeling that includes these factors could lead to different placements of health centers, potentially prioritizing locations that are more accessible considering the topography.

Moreover, the feasibility of upgrading existing facilities to meet the standards of Grade A primary healthcare centers is closely tied to budget constraints. Detailed cost analysis must be conducted in future analysis to evaluate the financial implications of renovating existing healthcare centers versus constructing new ones. This assessment can include the construction integrity of existing buildings, the cost of upgrading and introducing new medical technologies, and the necessary training for medical personnel. A budget-conscious approach might favor upgrading facilities where minor modifications can bring them up to standard, thereby preserving resources for regions where new facilities are desperately needed.

Besides, To assess the robustness of the model, scenario analysis can be invaluable. This involves testing the model under various hypothetical situations such as demographic changes, economic changes, and potential changes in healthcare policy. For instance, scenarios can be constructed to predict outcomes where there is a higher-than-expected population growth in certain areas, or where budget cuts limit the number of new centers that can be built. This type of analysis helps in understanding the flexibility and adaptability of the model under different future conditions, ensuring that the healthcare system remains resilient and responsive to change.

Last but not least, we have to consider the environmental impacts of the construction and operation of healthcare facilities, including changes in land use, increased waste production, and potential disruptions to local ecosystems. Given that Qiandongnan is situated in Southwestern China, a region predominantly affected by karst rocky desertification and recognized for its environmental fragility (Li et al., 2023; Dai et al., 2021), it is crucial for future studies to integrate Environmental Impact Assessments (EIA) into the planning process to mitigate adverse effects. EIA can include selecting construction materials and practices that minimize environmental degradation, designing energy-efficient buildings, and ensuring that new constructions comply with local and national environmental regulations. Moreover, the placement of healthcare facilities should consider ecological sensitivity, avoiding areas where construction could disrupt critical habitats or protected areas.

VII. Conclusion

In conclusion, this study successfully utilized the capacitated P-median model to optimize the distribution of primary medical centers in Southeastern Guizhou, China. The model not only gives advice in solving the shortage of health facilities due to the socioeconomic conditions but also improves the healthcare accessibility and efficiency. By determining optimal locations for 120 Grade A primary medical centers, we provided a data-driven method for policy decisions leading to enhanced medical service coverage and reduced travel distances for the majority of the rural population. Future efforts should integrate additional factors such as budget constraints, environmental impacts, and technological upgrades to ensure more sustainable and effective healthcare services. Through comprehensive planning and consideration of local conditions, the findings from this study contribute to the broader goals of equitable health service distribution and improved public health outcomes in underserved regions, especially for those areas with more poverty in China.

VIII. References

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