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Enhancing educational equity and sustainability: a fuzzy-based framework for optimal school site selection

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ABSTRACT
Educational equity is a crucial component of social fairness, essential for a harmonious society. This study employs Multi-Criteria Decision Analysis (MCDA), integrating Geographic Information Systems (GIS) and the Fuzzy Analytic Hierarchy Process (FAHP), to assess and improve the distribution of middle school resources in Henan Province, China. We applied fuzzy techniques simultaneously in the weighting and classification processes of school site selection criteria. We evaluated economic, transportation, social, and safety factors and incorporated educational resource allocation and teaching environment factors into the site selection criteria. Our study finds that over 39% of land in Henan Province is unsuitable for school construction. We also identified areas on the urban periphery and in the eastern and southern regions, which have convenient transportation and high educational demand, as potential sites for middle schools. Sensitivity analysis further validates the reasonableness of the expanded decision criteria. Our approach addresses the limitations of traditional AHP in handling fuzzy information, considers long-term resource allocation and ecological development of school operations, and provides planners with a robust framework for making scientifically informed site selection decisions, thereby promoting educational equity and sustainable development.

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Site selection; geographic information systems; fuzzy analytic hierarchy process; multi-criteria decision analysis; educational equity

1. Introduction

In the current era of globalization, education is considered a decisive factor driving a nation's economic growth and social progress (Brown and Lauder 1996). Through education, individuals acquire academic knowledge, moral values, social skills, and global awareness. Nations worldwide recognize the significance of education in enhancing the quality of their citizens, bolstering national competitiveness, and fostering global peace and development (Akkerman, Bakker, and Penuel 2021). Historically, due to insufficient widespread access to basic education, residents often focused solely on the overall educational level rather than the distribution of educational resources. This focus resulted in significant urban-rural disparities and regional differences within the international education system concerning educational infrastructure, teaching staff, education policies, and funding (Benavot

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2016; McFarland et al. 2019; World Bank 2018). As socio-economic conditions and urbanization continue to advance, societies are increasingly striving for balanced development across various sectors – including population and economy. Consequently, people are increasingly demanding an equitable distribution of educational resources and balanced educational development (Huang 2023). The previous approach of prioritizing resource allocation efficiency over fairness no longer aligns with contemporary educational ideals. This shift underscores the need to optimize the spatial distribution of educational resources. By employing scientific spatial planning and effective allocation, we can maximize the utilization of existing educational resources, ensure the long-term development of schools, and meet the growing student population and diverse educational needs.

School spatial planning is not merely a technical decision but a multifaceted process that requires balancing urban planning, educational equity, and environmental sustainability. Construction feasibility is a fundamental criterion in site selection, as factors such as land availability, topography, and infrastructure directly impact the efficiency of building construction and operation (Kim, Lee, and Moon 2018). Ideally, schools should be located in areas with flat terrain, well-developed infrastructure, and convenient transportation to minimize construction costs and maximize resource coverage. However, prioritizing construction feasibility alone may lead to an overconcentration of educational resources, exacerbating disparities in economically disadvantaged or geographically challenging areas. To ensure equal educational opportunities, site selection must account for the needs of underserved communities. Nevertheless, building schools in such areas often entails higher construction and maintenance costs, imposing financial pressure on local governments. Simultaneously, site selection must also consider environmental sustainability, ensuring that the school and its surroundings promote student health and learning quality (Brink et al. 2021; Sadrizadeh et al. 2022). Moreover, locations with evident construction constraints, frequent natural disasters, or disruptive environmental factors should be avoided (Moussa and Abou Elwafa 2017). Overall, school site selection is a complex decision-making process that requires comprehensive coordination. Planners must strike a balance between land-use efficiency, educational equity, and ecological sustainability, carefully weighing the specific constraints and interests of different scenarios to develop realistic and forward-looking spatial strategies. A structured approach is needed to support consistent and transparent decision-making across different scenarios.

Multi-Criteria Decision Analysis (MCDA) allows for comprehensive analysis and decision-making across a range of criteria and plans under the influence of multiple factors. Since the 1990s, the application of MCDA and Geographic Information Systems (GIS) has addressed numerous spatial issues related to land suitability, site selection, and resource assessment (Malczewski and Rinner 2015). This approach has been widely used in various scenarios, including landfill site selection (Aksoy and San 2019; Elkhrachy, Alhamami, and Alyami 2023), suburban agricultural land assessment (Yuan et al. 2022), wind farm site selection (Rekik and El Alimi 2023a, 2023b), hospital site selection (Boyacı and Şişman 2022), park site selection (Zavadskas, Bausys, and Mazonaviciute 2019), and urban development (Pourahmad et al. 2015; Rahman and Szabó 2022). In these studies, the Analytic Hierarchy Process (AHP) has been extensively used to establish criteria weights in site selection processes (Ahadi et al. 2023; Noorollahi et al. 2022; Zhang et al. 2020). Currently, there are fewer studies on school site selection and most of them employ a combination of AHP and GIS methods (Ahmed Ali 2018; Prasetyo, Mohamad, and Fauzi 2018). For example, Samad et al. (2012) used GIS and AHP in northern Malaysia to evaluate land costs, access roads, and environmental conditions, developing suitability maps. Talam and Ngigi (2015) conducted a multi-criteria evaluation for primary school site selection in Kenya using GIS and MCDA, considering factors such as terrain, land use, and population density, and proposed optimized site selection plans. However, traditional AHP has limitations in handling fuzzy information and uncertainty. In real-world decision-making environments, qualitative assessments, subjective judgments, and challenges in quantifying uncertainty are often involved, particularly in school site selection. Many decision criteria inherently possess ambiguity, yet traditional AHP relies on decision-makers assigning precise numerical weights to these criteria. This rigidity can lead to information loss or cognitive bias, potentially affecting the reliability of the decision-making process. In recent years, the Fuzzy Analytic Hierarchy Process (FAHP) has been introduced to address these limitations by incorporating fuzzy logic. Some studies have used FAHP combined with GIS to apply fuzzy techniques in determining criteria weights or classifications, demonstrating its applicability in multi-criteria decision-making (Boonmee and Thoenburin 2024; Fard et al. 2022; Zhang, Shen, and Li 2018). Nonetheless, the application of fuzzy techniques in school site selection is rare and has mainly been limited to criteria weighting. Therefore, we innovatively incorporate fuzzy theory into both the weighting and classification processes of school site selection criteria.

An extensive review of the literature on school site selection indicates that most studies primarily consider traditional factors such as infrastructure, population, environment, and physical criteria (Bukhari, Rodzi, and Noordin 2010; Moussa and Abou Elwafa 2017; Samad et al. 2012). However, ensuring the long-term operation and optimal educational outcomes of a school necessitates a comprehensive assessment of the distribution of existing educational resources and environmental impacts (Greenwald, Hedges, and Laine 1996; Tucker and Izadpanahi 2017). To address this, we introduce educational resource allocation and teaching environment factors into the school site selection process. Notably, we include 'accessibility to existing schools' and 'the number of schools per thousand students' in the site selection criteria for the first time.

In this study, we employed a GIS-based Multi-Criteria Decision Analysis (MCDA) method to generate suitability maps for middle school site selection and to identify optimal locations for new schools. We conducted a comprehensive evaluation from the perspectives of administrators and users – including government officials, students, and teachers – considering factors such as campus construction, safety, existing resources, environment, and distance. We identified three main evaluation criteria, i.e. distance factors, social factors, and environmental factors. By integrating the FAHP with GIS, we reduced subjectivity in the decision-making process. Additionally, our incorporation of educational resource allocation and teaching environment factors into the site selection criteria enhances the scientific rigor and rationality of the process, promoting educational equity and environmental sustainability. Finally, we performed a sensitivity analysis to test the stability of the site selection results. The suitability maps generated by this study provide planners with a scientifically sound basis for making site selection decisions.

2. Materials and methods

2.1. Study area

The study area is situated within Henan Province, which is located in central China, has a geographical location between 110°21'E~116°39'E, 25°39'N~26°05'N. Henan has jurisdiction over 18 cities, with an area of 165,700 km^2, it is characterized by diverse landforms, with mountains, plains, basins, rivers, and other geomorphic units interspersed. Henan is an inland province and also an important economic development region in China (Shen et al. 2017). As of 2022, there were 49,900 schools of various levels and types in Henan, catering to an educational population of 287.86 million, constituting 29.16% of the total population (Henan Provincial Department of Education 2022). By 2025, Henan will add 400,000 senior middle school places with each new school limited to a maximum of 3,000 students, according to Henan's 14th Five-Year Plan for Educational Development (People's Government of Henan Province 2021). How to scientifically plan and site schools to meet the needs of the students has become a practical problem that needs to be solved.

2.2. Determination of school site selection criteria

2.2.1. Criteria selection

In addition to the basic elements of school site selection, such as construction conditions, safety, and population, we also considered the distribution of educational resources, population demand,

and environmental quality, such as accessibility to existing schools, the number of schools per thousand students, NDVI, and PM2.5. This comprehensive approach to site selection not only ensures the basic needs for school construction but also promotes educational equity and environmental sustainability, enhancing the scientific and rational aspects of campus site selection. After considering field conditions, existing research, and expert opinions, we divided the middle school site selection criteria into three categories: distance factors, social factors, and environmental factors, with a total of 13 sub-criteria. We included the distance from malls, office buildings, factories, highways, and main roads, and accessibility to existing schools as distance factors; population density, the number of schools per thousand students, and economic level as social factors; slope, drainage density, NDVI, and PM2.5 as environmental factors.

Schools should not be located in highly commercialized areas or too close to heavily trafficked zones. Commercial districts, busy streets, and factories often generate dust, noise, physical hazards, and chemical risks, which can negatively impact student health and learning outcomes (Moussa and Abou Elwafa 2017; Talam and Ngigi 2015). Malls and commercial areas tend to attract heavy vehicular and pedestrian traffic, which not only increases the risk of road crashes – especially for students walking or cycling – but also contributes to noise and air pollution (Stoker et al. 2015; Yuan et al. 2019). These factors can distract students and disrupt the learning environment, making such areas unsuitable for school placement. Furthermore, commercial zones may have higher crime rates, which raises security concerns for students and staff (Samad et al. 2012). Given these risks, schools should be located at a reasonable distance from major commercial hubs to ensure a safer and more conducive learning environment. Additionally, The selection of new school sites should also avoid resource duplication or excessive concentration of educational facilities, ensuring that new schools effectively serve underserved communities rather than adding to already well-served areas. To assess educational accessibility, we used Accessmod5 to evaluate gaps in school coverage and determine the quality of commuting routes (Figure 1 (f)).

Higher population density typically correlates with a larger pool of potential students and a greater demand for school capacity and educational resources. Previous studies shown socioeconomic status (SES) significantly affects educational outcomes, as wealthier neighborhoods generally have better educational infrastructure and support systems (Owens, Reardon, and Jencks 2016). To quantify economic disparities, we used nighttime lighting data as a proxy for economic level, as it reflects urban development and household wealth distribution (Chen and Nordhaus 2011; Sutton, Elvidge, and Ghosh 2007). Schools should be strategically distributed across both high – and low-income areas to promote educational equity and ensure that all students have access to quality educational resources regardless of their socio-economic background.

Given the mountainous terrain in the western part of the study area, steeper slopes increase the complexity and cost of construction, and nearby areas are more susceptible to natural disasters such as landslides and rockfalls. This study measures terrain stability using slope values and excludes areas with slopes greater than 15 degrees. Drainage density is another key factor; higher drainage density indicates greater runoff, which may lead to severe flooding hazards (Kapilan and Elangovan 2018). PM2.5 levels, a key indicator of air quality, are used to assess environmental health, with a threshold of 75 $\mu g/m^3$ in accordance with the Chinese 'Ambient Air Quality Standard' (Wei et al. 2021). Additionally, areas with higher NDVI values contribute to better air quality and temperature regulation, promoting physical activities and outdoor engagement for students.

2.2.2. Restriction determination

Restrictions are based on Boolean relationships (true/false) and confine the study area to specific locations. Determination of restrictions for school construction in the study area is performed, creating corresponding restriction layers. A restriction map is computed through the multiplication of all restriction layers. We established four restrictions: distance from existing schools, distance from water bodies, distance from airports, and distance from historical sites. A buffer of a specified width is created for each restriction.

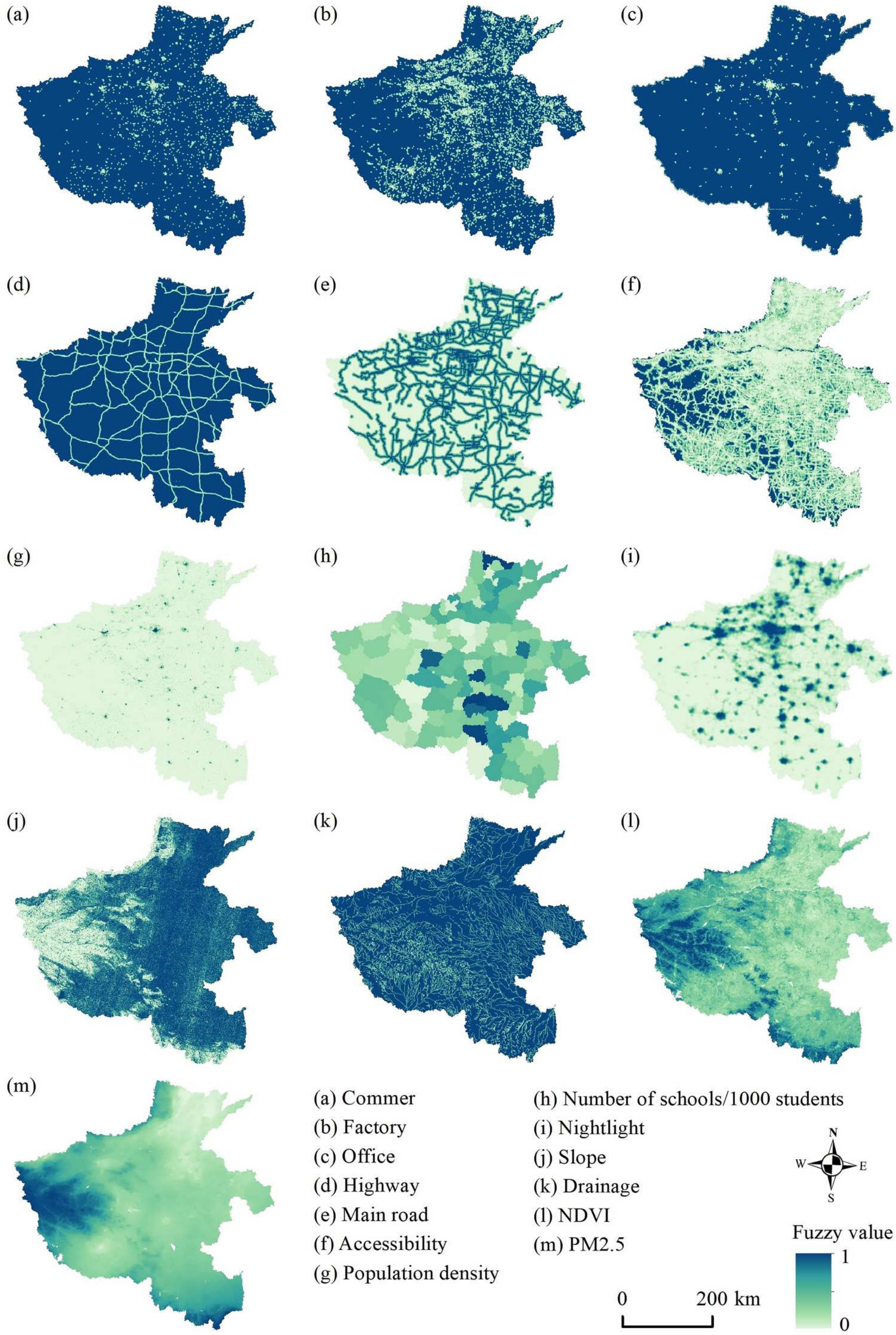


Figure 1. Factors relevant for determining the location of schools in Henan, China.

We generated four restriction layers based on the defined restrictions (Figure 2) and created a binary GIS grid for each restriction. Within the restriction area, grid cells were designated as ‘0’, while the remaining cells were designated as ‘1’. Only cells in the restriction map with a value of

'1' hold a non-zero value in the constraint map. This indicates that these cells satisfy all the restrictions and can be further considered. Non-potential areas should be removed from the initial suitability map to enhance the accuracy of site selection.

This study relies on various data sources, including satellite imagery, websites, and statistical datasets. The hydrological data utilized in the study are derived from the 1km × 1 km drainage density of the 2019 China Scientific Data platform, from the third national land survey as the data source, and river network density defined by calculating the drainage density. Elevation data were obtained from the 2022 Copernicus DEM to generate slope data in ArcGIS 10.8. The nightlight data were corrected DMSP-OLS-like data for 2021 obtained by integrating DMSP-OLS and SNPP-VIIRS data (Wu et al. 2021). Air pollution information was selected from the 2021 PM2.5 data in the China High Air Pollutant (CHAP) dataset. The Normalized Difference Vegetation Index (NDVI) data were provided by NASA's MOD13A3 Dataset. Population distribution was based on the LandScan population density dataset (Dobson et al. 2000). Middle schools, commercial centers, industrial facilities, office complexes, and historical sites were derived from the 2022 Gaode Map POI data. Road network data were sourced from the 2021 Open Street Map (OSM). Additionally, the text data included educational statistics from the 18 cities and prefectures of Henan Province, as reported in the 2021 Henan Statistical Yearbook. All collected raw data were initially processed and converted into raster data layers, with a uniform resolution of 1 km × 1 km. GIS

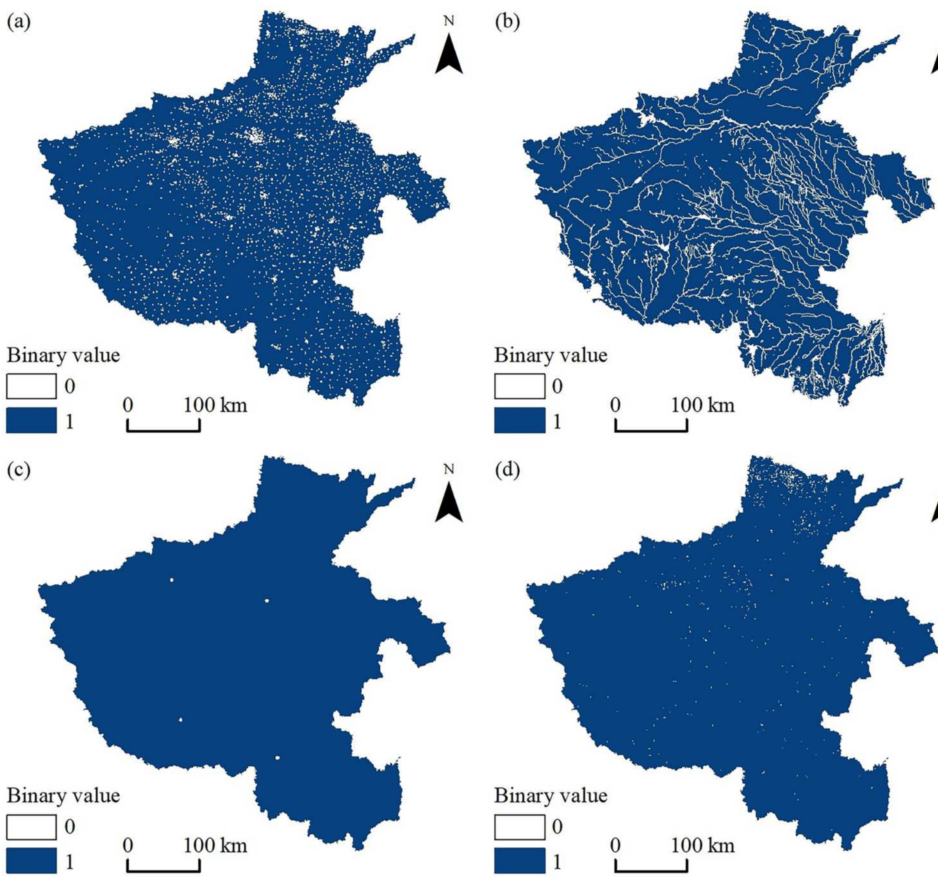


Figure 2. Restriction layers. (a) Distance from existing schools (buffer = 1 km). (b) Distance from water bodies (buffer = 1 km). (c) Distance from airports (buffer = 3 km). (d) Distance from historical sites (buffer = 1 km).

techniques were employed to calculate the school land suitability index for each raster cell, producing a raster map that represents school land suitability across Henan.

2.4. Fuzzy standardization

We employ fuzzy logic to standardize each layer. Where each element is assigned membership degrees, forming a fuzzy set. The membership values, typically between [0, 1], are determined using fuzzy functions such as linear, triangular, or trapezoidal functions(Yousefi, Hafeznia, and Yousefi-Sahzabi 2018). The 13 sub-criteria for middle school site selection were standardized using the raster calculator and fuzzy membership tools within ArcGIS, normalizing values to a range of 0–1. A membership degree of 0 indicates minimal suitability, while 1 indicates maximum suitability based on each sub-criterion. The mathematical equations for the fuzzy functions are provided in Table 2, and the membership functions for each criterion are outlined in Table 1. The resulting fuzzy raster layers are shown in Figure 1.

2.5. Criteria calculation

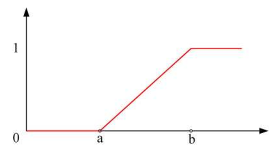
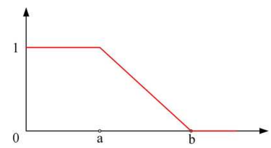
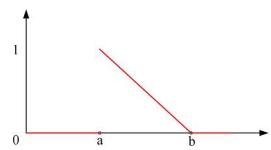
Fuzzy hierarchical analysis (FAHP) was used to determine the weights of the main and sub-criteria for school site selection. Unlike traditional AHP, which suits deterministic problems, FAHP integrates fuzzy logic to address complex decisions. We established a fuzzy reciprocal judgment matrix $A = (a_{ij})_{n\times n}$, where for any $i, j = 1, 2, \ldots, n$, with $a_{ii} = 0.5$ and $i, j = 1, 2, \ldots, n$, $0 < a_{ij} < 1, a_{ij} + a_{ji} = 1$. Constructing the fuzzy reciprocal judgment matrix involves using comparison scales (a_{ij}) to represent the relative importance of elements a_i and a_j at the same level to the element at the upper level. To quantify the importance of site selection criteria, we consulted eight experts specializing in educational planning, GIS, urban development, and multi-criteria decision-making. The evaluation was conducted using a fuzzy scale ranging from 0.1–0.9, which represents nine levels of relative importance. Specifically, a value of 0.5 denotes equal importance, while 0.6, 0.7, 0.8, and 0.9 indicate increasing levels of significance, corresponding to 'moderately important,' 'very important,' 'extremely important,' and 'absolutely important,' respectively. Conversely, values between 0.1-0.4 represent the importance of a_j compared to a_i, with smaller values representing higher importance. To ensure the logical consistency of the derived weight scores, we computed the consistency ratio (CR) within the FAHP. A CR value below 0.1 signifies acceptable consistency, whereas a value exceeding this threshold indicates the need for scale adjustments (Saaty 1977). Based on the expert evaluations, we subsequently determined the weight distributions for both the primary and sub-criteria.

Table 1. Membership functions and fuzzification parameters of criteria layers.

Criterion	Sub-criterion	Fuzzy membership function	a	b
Distance factors	Distance to commercial area	Ascending	300	2000
	Distance to industrial area	Ascending	500	2000
	Distance to office building	Ascending	300	2000
	Distance to highway	Ascending	100	2000
	Distance to main road	Descending (2)	100	5000
	Accessibility to existing schools	Descending (1)	min	max
Social factors	Population density	Ascending	min	max
	Number of schools/1000 students	Descending (1)	min	max
	Economic level	Ascending	min	max
Environmental factors	Slope	Descending (1)	1	15
	Drainage density	Descending (1)	min	max
	NDVI	Ascending	0	1
	PM2.5	Descending (1)	35	75

Note: min – Minimum value of the map. max – Maximum value of the map.

Table 2. Fuzzy membership function.

Function type	Mathematical equation	Fuzzy function figures
FuzzyLinear Ascending	$\mu(x)=\begin{cases}0 & x\le a\\ \frac{x-a}{b-a} & a<x<b\\ 1 & x\ge b\end{cases}$	
FuzzyLinear Descending (1)	$\mu(x)=\begin{cases}1 & x\le a\\ \frac{x-b}{a-b} & a<x<b\\ 0 & x\ge b\end{cases}$	
FuzzyLinear Descending (2)	$\mu(x)=\begin{cases}0 & x\le a\\ \frac{x-b}{a-b} & a<x<b\\ 0 & x\ge b\end{cases}$	

Assuming the constructed fuzzy judgment matrix is $A_k=(a_{ij}^k)_{n\times n}(k=1,\ 2,\ \ldots,\ s)$, when $a_{ij}=\sum_{k=1}^{s}\lambda_k a_{ij}^k,\ \lambda_k>0,\ \sum_{k=1}^{s}\lambda_k=1$, it is considered that $\bar{A}=(\bar{a}_{ij})_{n\times n}$ represents the composite matrix of A_k. Additionally, the sorting vector $\bar{W}=(\bar{w}_1,\ \bar{w}_2,\ \ldots,\ \bar{w}_n)^T$ derived from the minimum variance for $\bar{A}$ satisfies the following:

$$\bar{w}_i=\frac{1}{n}\left(\sum_{k=1}^{s}\sum_{j=1}^{n}\lambda_k a_{ij}^k+1-\frac{n}{2}\right),\ \ i,\ j=1,2,\ldots,n \tag{1}$$

When $\sum_{j=1}^{n}a_{ij}\le\frac{n}{2}-1$, the weights w shows negative and zero values, indicating the need for experts reassessment. When $\sum_{j=1}^{n}a_{ij}>\frac{n}{2}-1$, the weights for each hierarchical standard can be determined using the constructed fuzzy complementary judgment matrix (Eq. 1). These are then combined using the geometric mean method, and the composite weights are normalized to obtain the final weights.

2.6. Map calculation

The Weighted Linear Combination (WLC) method combines primary and sub-criteria raster layers by assigning the calculated weights (Section 2.5) to the respective layers (Moeinaddini et al. 2010). Based on the weights calculated for each criterion in Section 2.5, the ArcGIS raster calculator tool is used to generate the initial suitability map. The Suitability Index (SSI, S_k) is calculated using the formula:

$$S_k=\sum_{i=1}^{n}W_iN_{ki} \tag{2}$$

Where S_k represents the ranking of the suitability map, W_i stands for the weight of evaluation criterion i, N_{ki} denotes the score of cell k under criterion i, and n signifies the number of selected evaluation criteria.

3. Results

3.1. Site suitability analysis of middle schools in Henan Province

We used the FAHP method to establish the weights of various factors for campus site selection based on expert scoring (Table 3). The results show that among the three main criteria, environmental factors have the highest weight, while social factors have the lowest. Within environmental factors, slope, NDVI, and PM2.5 have similar weights, except for drainage density. Accessibility to existing schools, the number of schools per thousand students, and drainage density all have relatively high weights, highlighting the significant influence of educational resource distribution and physical construction conditions on school location selection. Additionally, we conducted a comparative analysis of AHP and FAHP, revealing that while both methods produce similar rankings, FAHP yields a smoother weight distribution and reduces extreme variations observed in AHP. The higher CR values in AHP indicate weaker consistency and greater susceptibility to subjective bias.

We created thematic suitability maps for distance factors, social factors, and environmental factors, and further integrated them into an initial suitability map (Figure 3(a)). After excluding all restricted areas (Figure 3(b)), we obtained the final site suitability map (Figure 3(c)). The most suitable locations for middle school sites are indicated in red, representing the highest values. The least suitable sites are shown in blue, indicating the lowest values. Based on the spatial overlay results of the 13 criteria, the site selection area is categorized into highly suitable, more suitable, moderately suitable, less suitable, and unsuitable zones. From the suitability zoning in the research area, it appears that the suitability zones for middle school site selection in Henan Province are primarily more suitable and moderately suitable. Approximately 5.09% (8500 km^2) of middle school site selections are highly suitable, 55.53% (92735 km^2) are more suitable, 20.70% (34569 km^2) are moderately suitable, 0.65% (1086 km^2) are less suitable, and 18.03% (30110 km^2) are unsuitable. The more suitable areas are concentrated in the eastern and southern parts of Henan Province, where the environmental (NDVI and PM2.5) and topographical conditions align relatively well with the site selection requirements. The most suitable areas are clustered in adjacent regions near some city centers. Apart from fulfilling the aforementioned conditions, these areas often possess higher accessibility, construction conditions, and potential student populations. However, they tend to lag in educational resources, indicating potential for middle school campus selection. Most of the unsuitable areas for middle school site selection are encompassed by water bodies and the central regions of various cities.

Table 3. Weights of all criteria used in site selection.

	Weight			CR		Weight	
Criteria	AHP	FAHP	Sub-criteria	AHP	FAHP	AHP	FAHP
Distance factors	0.378	0.330	Distance to commercial area	0.062	0.025	0.175	0.158
			Distance to industrial area			0.153	0.155
			Distance to office building			0.211	0.184
			Distance to highway			0.133	0.150
			Distance to main road			0.143	0.163
			Accessibility to existing schools			0.185	0.190
Social factors	0.252	0.277	Population density	0.076	0.037	0.325	0.299
			Number of schools/1,000 students			0.372	0.360
			Economic level			0.303	0.341
Environmental factors	0.380	0.393	Slope	0.023	0.000	0.264	0.245
			Drainage density			0.292	0.278
			NDVI			0.206	0.229
			PM2.5			0.238	0.248
CR	*CR of AHP* = 0.043, *CR of FAHP* = 0.014.						

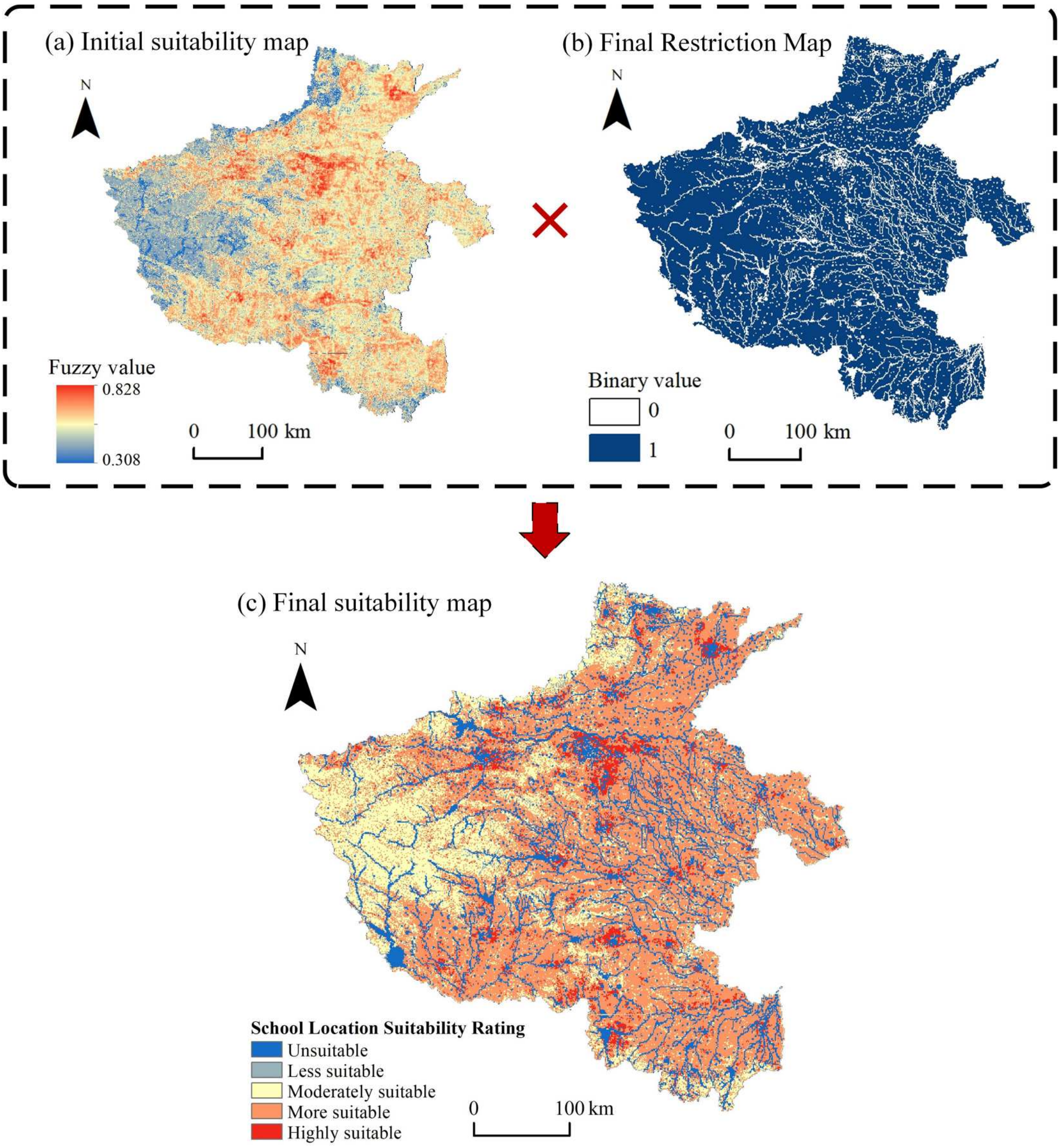


Figure 3. The final map of suitability site selection for middle schools. (a) Initial suitability map. (b) Final restriction map. (c) Final suitability map, where red areas indicate highly suitable regions for school construction, while blue areas represent the least suitable locations.

We also calculated the suitability statistics for different prefecture-level administrative divisions in Henan Province. Zhengzhou City (1387 km^2), Nanyang City (1112 km^2), and Xinyang City (1154 km^2) rank as the top three areas highly suitable for middle school site selection. This ranking is heavily influenced by the size of the administrative area, indicating that these cities have more land available for middle school construction. Among them, Zhengzhou City has the highest proportion of land area (18.3%) with substantial potential for middle school site selection. As depicted in Figure 3(c), the northeast and southeast corners of Zhengzhou City, the northeast corner of Luoyang City, the western side of Xinyang City, as well as the peripheries of Puyang City, Xinxiang City, Zhoukou City, and Zhumadian City, are potential areas for future middle school site selection in Henan Province.

3.2. Sensitivity analysis

A sensitivity analysis was used to check the stability of the results and the subjectivity of expert judgments (Mészáros and Rapcsák 1996), further examining the impact of changes in standard weights on the overall suitability index. The sensitivity analysis aims to determine which standards play a key role in forming the decision results, mainly by altering the standard weights (Mardani et al. 2017). We constructed four comparative scenarios: a baseline scenario (where all criteria are equally weighted) and three single-factor control scenarios (where the weights of distance, social, and environmental factors were set to zero, respectively). In the control scenarios, when a specific criterion was excluded, the original weight proportions of the remaining criteria were maintained.

As shown in Figure 4, notable disparities exist in suitability values across different weighting scenarios, which is expected given that the criteria are selected based on the specific characteristics of the study area. In Case 2, most areas in the western part of the study region were evaluated as unsuitable for middle school construction. This region is economically underdeveloped, with poor accessibility to existing schools (Figure 1(f)). The removal of the 'distance' factor further reduced its suitability, highlighting the critical role of transportation accessibility in ensuring educational equity, particularly for rural students. Meanwhile, increasing the weights of environmental

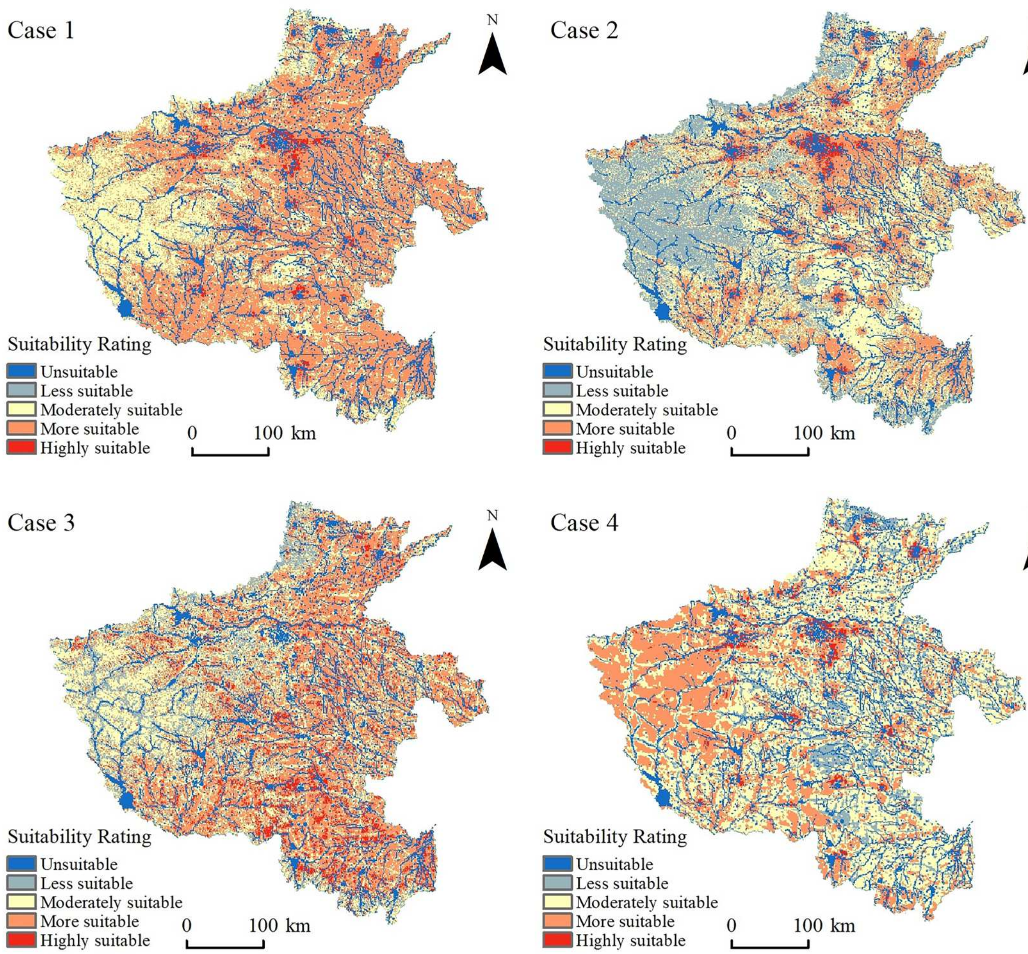


Figure 4. Impact of Standard Weight Adjustment on the Overall Suitability Index. Case 1: equal weight. Case 2: Distance factors weight = 0. Case 3: Social factors weight = 0. Case 4: Environmental factors weight = 0.

and social factors shifted the suitable locations toward areas with better environmental quality, more stable terrain, and stronger economic development.

In Case 4, after excluding the 'environmental factors,' the suitability of the western region significantly increased, primarily due to the diminished influence of slope (Figure 1(m)). Slope is a key factor in school siting studies, as steeper terrain often entails higher construction and maintenance costs, along with potential safety risks. Although steep-slope areas are generally deprioritized for school construction due to geographical constraints, these regions still require schools to meet the educational needs of local youth. Therefore, school siting decisions should not simply exclude high-slope areas; instead, a balance should be sought between slope and transportation accessibility to control construction costs while ensuring adequate educational service coverage.

Moreover, the stability of suitability assessments varies significantly across different geographic contexts. In densely populated or economically developed urban areas, school site suitability remains relatively stable under different weighting schemes. However, in sparsely populated or geographically constrained areas, even slight adjustments in weights can lead to substantial changes in suitability rankings. In urban areas, the high redundancy of infrastructure – including road networks and public services – establishes interference-resistant resilience in site-selection systems, effectively mitigating fluctuations caused by variations in weighting schemes. In contrast, underdeveloped regions often rely on a single dominant factor, amplifying the sensitivity of decision parameters and exposing vulnerabilities in regional development.

4. Discussion

This study presents an innovative evaluation framework that integrates the FAHP with MCDA to assess the suitability of constructing middle school campuses across Henan Province, China. By establishing comprehensive and rational evaluation criteria, we aim to provide clear guidance and recommendations for optimizing high school educational resources in the region. Our findings reveal that over 39% of the land in Henan Province lacks significant advantages for educational infrastructure development. The areas deemed most suitable for new educational infrastructure are primarily concentrated on the urban peripheries in the eastern and southern parts of the province.

Compared to existing studies on educational resource evaluation, our research introduces the application of FAHP in both the weighting and classification processes, offering a novel approach to incorporating uncertainty in human decision-making. Traditional studies have predominantly utilized the AHP to calculate the weights of evaluation criteria (Mohammadı and Hosseınalı 2019; Talam and Ngigi 2015). However, AHP requires decision-makers to assign precise numerical values to represent the relative importance of each criterion, which often oversimplifies real-world problems characterized by linguistic uncertainty, overlapping criterion boundaries, and subjective expert judgment. School site selection, in particular, involves multiple uncertain factors, many of which inherently exhibit a degree of fuzziness. To overcome these limitations, the FAHP replaces exact numerical scales with fuzzy numbers, constructing a fuzzy judgment matrix that better accounts for the inherent uncertainty and imprecision in decision-making. This approach reduces judgment errors and enhances the reliability and consistency of the results. Furthermore, FAHP has been widely applied in various MCDA contexts, such as infrastructure planning and environmental assessment, demonstrating its robustness in handling complex spatial decision problems (Boonmee and Thoenburin 2024; Rekik and El Alimi 2023a, 2023b). Its application in school site selection further validates its suitability for educational resource allocation.

Furthermore, we have innovatively incorporated new evaluation criteria such as existing school accessibility, the number of schools per thousand students, NDVI, and PM2.5 concentration to ensure a more accurate and comprehensive assessment. Previous studies have typically focused on factors like physical conditions, population density, land use, and economic factors (Moussa and Abou Elwafa 2017; Prasetyo, Mohamad, and Fauzi 2018; Talam and Ngigi 2015). However, these criteria alone are insufficient to address the specific challenges in Henan Province. In the province's remote southern and western regions, the number of primary and secondary schools and the quality of educational facilities are significantly lower than in the more developed central and eastern areas. In some rural communities, students commute more than 10 kilometers daily, highlighting the necessity of considering educational equity in school siting. By incorporating existing school accessibility and the number of schools per thousand students into our evaluation criteria, we aim to reduce students' commuting time and costs, balance educational resource distribution, and promote regional educational equity. Additionally, the importance of environmental quality in supporting students' health and well-being must be considered. Integrating NDVI and PM2.5 concentration as indicators of environmental sustainability in educational planning contributes to the development of more sustainable and eco-friendly educational infrastructure. A high NDVI value indicates greater vegetation coverage and green spaces, which have been shown to enhance environmental experiences, provide recreational opportunities, reduce noise, and improve mental health (Brown, Schebella, and Weber 2014; Hartig, Mang, and Evans 1991; Nassauer 1995). Higher NDVI values are also associated with reduced urban heat island effects and improved microclimate conditions, offering students a more comfortable learning environment (Maroni et al. 2021; Wang et al. 2022). Similarly, lower PM2.5 concentrations indicate better air quality, which is crucial for safeguarding students' respiratory health, cognitive function, and mental well-being (Ke et al. 2022; Liu et al. 2017; Lyons et al. 2024). By introducing multiple new evaluation criteria, the school siting process becomes more scientific and comprehensive, integrating considerations of educational equity, environmental health, and sustainable development. This approach provides more precise and actionable decision-making support for future educational resource allocation and urban planning.

The sensitivity analysis results highlight the complexity of school site selection, shaped by competing priorities. While factors such as slope, road density, and environmental conditions influence construction feasibility and long-term sustainability, addressing educational inequality requires prioritizing access for underserved communities. These areas often face both economic and infrastructural disadvantages, yet they are most in need of investment in educational resources. This trade-off underscores the challenge of balancing cost-effective construction with equitable resource distribution. By using sensitivity analysis to test different weighting schemes, policymakers can refine site selection strategies and adjust policies to favor more equitable distribution of schools. Flexible site selection criteria and innovative construction methods can enable schools to be built in challenging terrains, helping to bridge gaps in educational opportunity while maintaining infrastructure resilience.

The findings of this study have significant policy implications for educational planning and sustainable development in Henan Province, as well as other regions facing similar challenges. The results indicate an urgent need for government interventions to promote equitable resource distribution. Policymakers should prioritize the development of new schools in the under-resourced southern and western regions to reduce regional educational disparities and ensure that all students have equitable access to quality education. Adopting a multi-perspective approach that considers the government, schools, and students, this study systematically evaluates the feasibility, equity, and sustainability of school construction. Furthermore, it develops a MCDA framework that integrates GIS and fuzzy theory. We encourage educational planners and decision-makers to adopt this approach to enhance the reliability and consistency of school site selection, thereby providing theoretical and technical support for the rational allocation of educational infrastructure.

Despite the contributions of this study, there are areas where further research is warranted. The accuracy of the weighted linear overlay method is contingent upon the precision of spatial data. Although variables such as NDVI and slope inherently have higher resolutions, all layers were standardized to a 1 km × 1 km resolution to ensure comprehensive coverage of all key variables. Our results demonstrate that this resolution is suitable for identifying macro-scale suitability patterns and prioritizing areas for further optimization in provincial-level analyses while maintaining a feasible computational workload. However, in urban environments, this relatively coarse resolution limits the detection of micro-scale geographic features, such as small streams, narrow roads, and subtle topographic variations. Future research should incorporate higher-resolution datasets in urban or ecologically sensitive areas to refine exclusion criteria and enhance spatial accuracy. The sensitivity analysis focused on individual criteria without fully exploring interactions between sub-criteria. Expanding the range and number of scenarios in future sensitivity analyses could help to understand the complex interplay of factors and enhance the robustness of the evaluation. Additionally, while fuzzy AHP reduces judgment bias, the expert-driven weighting process still retains inherent subjectivity. To mitigate this, we incorporated consistency checks and fuzzy evaluation methods to reduce subjective variability. Future implementations could further enhance accuracy by expanding the expert panel, adopting the Delphi consensus technique, or integrating machine learning methods for improved weighting reliability. Moreover, we did not incorporate economic considerations such as construction costs, land prices, or maintenance challenges into the suitability assessment. Future research should integrate economic factors to provide a more comprehensive evaluation that balances cost-effectiveness with optimal site selection. While the study provides actionable insights, practical implementation may face challenges such as budget constraints, bureaucratic hurdles, and local opposition. Exploring strategies to address these challenges, perhaps through case studies or pilot projects, would be beneficial.

5. Conclusion

This study presents a comprehensive decision analysis framework that integrates the FAHP, Boolean logic, and GIS to evaluate the suitability of middle school sites in Henan Province, China. By generating a detailed suitability map for middle school location selection, we provide valuable insights for educational planners and policymakers. In calculating the weights of decision criteria, we incorporated qualitative data through expert evaluations collected via questionnaires, introducing fuzzy theory to construct the judgment matrix and effectively mitigating judgment errors in the decision-making process. Furthermore, we expanded the decision criteria to include considerations of long-term resource allocation and ecological development for schools, offering thorough explanations for the newly added criteria. The final suitability map revealed that over 39% of Henan Province lacks clear advantages for middle school construction. The optimal sites are primarily located in areas adjacent to most cities and city centers, as well as in flat, accessible regions with high educational demand in the eastern, southern, and southwestern parts of the province. Sensitivity analysis, conducted by adjusting the criterion weights, indicated that each criterion significantly impacts the evaluation results, further validating the rationale for expanding the decision criteria. The unique contribution of this study lies in optimizing the current decision-making process for educational resource distribution, thereby enhancing the accuracy and comprehensiveness of site suitability assessments. By integrating fuzzy logic into both the weighting and classification processes and considering long-term and ecological factors, we offer a more robust framework for school site selection. For future research, we recommend focusing on improving the spatial resolution of data in the decision-making process, addressing interactions between decision criteria, and exploring methods to balance cost and suitability. These efforts will provide more scientifically grounded recommendations for middle school site selection, further promoting educational equity and sustainable development.

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Availability of data and materials

Research data will be made available upon request.

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