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Resilience Assessment and Improvement Strategies for Urban Haze Disasters Based on Resident Activity Characteristics: A Case Study of Gaoyou, China

Yang Cao [1], Tingting Yang [2,*], Hao Wu [2], Shuqi Yan [2], Huadong Yang [2], Chengying Zhu [2] and Yan Liu [2]

[1] College of Construction Engineering, Jiangsu Open University, Nanjing 210019, China; caoyang@jsou.edu.cn
[2] Key Laboratory of Transportation Meteorology of China Meteorological Administration, Nanjing Joint Institute for Atmospheric Sciences, Nanjing 210041, China; haowu@cma.gov.cn (H.W.); yansq@cma.gov.cn (S.Y.); yanghd@cma.gov.cn (H.Y.); cherrinzhu@163.com (C.Z.); yanliu@cma.gov.cn (Y.L.)
* Correspondence: yangtt@cma.gov.cn

Abstract: The popularisation of mobile information technology has provided access to the living habits and activity trajectories of residents and enabled the accurate measurement of the impact of urban haze disasters on residents' lives, supporting urban haze risk response. Using the main urban area of Gaoyou City as a case study, this study identifies the spatial range and trajectory characteristics of the daily activities of residents in a haze disaster environment, based on air pollution monitoring and resident travel positioning data. We constructed an evaluation index system to measure the corresponding relationship between residential activities and haze disasters. The results indicate that the interference with residential activities and the adaptability of built environments are key indicators for evaluating urban resilience in haze environments, with weights of 0.57 and 0.43, and correlation indices of 0.67 and 0.81, respectively. The interference with residential activities and the adaptability of built environments exhibit spatial characteristics of cold and hot 'multi-core' agglomeration and 'strip' agglomeration, respectively. Specific indicators show that the residential activity exposure index is significantly influenced by the built environment factor index, with the vegetation coverage index showing a significant positive correlation (0.837) and the public transportation facility accessibility index showing a significant negative correlation (−1.242). Planning should focus on improving the adaptability of the built environment or reducing the interference with residential activities and enhancing the matching degree of the two at the spatial facility level.

Keywords: haze disasters; resilient cities; activity space; optimisation strategy; Gaoyou

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1. Introduction

With the continuous acceleration of urbanisation, China's urban scale and population density are rapidly increasing. New problems, such as global climate change and urban environmental pollution, are constantly emerging and disaster risks to cities are becoming increasingly severe [1]. The sustainable development of cities faces severe challenges as open and complex giant systems [2]. The third United Nations Conference on Housing and Sustainable Urban Development published the New Urban Agenda in 2016, advocating for 'urban ecology and resilience' as the core issues of new urban development [3]. In the 2023 Global Risk Report, the probability and potential impact rankings of environmental risk factors (such as extreme weather and natural disasters) are relatively high [4]. Owing to the increasing impact of natural disaster risks on cities, cities must strengthen their ability to resist, mitigate, and adapt to these risks. Resilience adaptation systems for urban responses to disaster environments have become a popular topic in fields such as urban planning, urban geography, disaster science, and ecology [3–5].

Urban resilience refers to the ability to resist, adapt to, and recover from external pressures, disturbances, or uncertainties, without disrupting basic organisational structures and functional systems [6]. As an early research field, disaster resilience has achieved many results through the expansion of resilience theory and practical exploration. Research mainly focuses on the repair capabilities of cities in coping with disasters through self-learning, adaptation, and self-organisation [7], including multiple dimensions, such as the active response, dynamic adjustment, and feedback improvement of cities to natural disasters [8]. Mileti first explained the concept of resilience from the perspective of disaster science, believing that disaster resilience is an acceptable level of regional losses from extreme natural disasters, and that disaster protection levels and disaster reduction measures need to be strengthened simultaneously [9]. The United Nations International Strategy for Disaster Reduction also defines disaster resilience as the ability of systems, communities, or societies exposed to disaster-causing factors to speedily and effectively resist, absorb, and withstand the impact of disasters and recover from them [10]. Some scholars have distinguished between the dynamic and static characteristics of disaster resilience, based on the different stages of a disaster, and devised an indicator system to quantitatively evaluate the ability of cities to adjust, adapt, recover, and rebuild after a disaster [11]. Based on a review of research on disaster resilience, both domestically and internationally, some scholars believe that urban natural disaster resilience refers to the ability of a city to absorb, respond to, protect, and restore the lives, livelihoods, and corresponding infrastructure of its residents without compromising its long-term development goals when encountering natural disasters [12].

With the increasing frequency of natural urban disasters, countries worldwide have developed a set of resilient urban construction models and governance systems to cope with the adverse effects of natural disasters on urban development [13]. The Rockefeller Foundation, the World Bank, the United Nations Disaster Reduction Programme, and other organisations have established a research framework for resilient cities to address climate change and reduce disaster risks [13]. Countries worldwide have launched targeted and resilient urban governance practices to respond to climate change and disaster risks. For example, New York City in the United States has developed a resilient governance system to cope with natural disasters, such as floods and storm surges [14]. The London government introduced policies for risk management, urban resilience enhancement, and corresponding adaptive implementation paths [15]. The evaluation of urban disaster resilience is also a focus of academic attention, and current resilience evaluation systems mainly include engineering and comprehensive types of analysis [16]. Among them, the study of engineering indicator systems focuses on the adaptability of a single disaster-bearing entity to specific disasters, such as the resilience repair ability of infrastructure in disaster environments, such as earthquakes, fires, and hurricanes [17–19]. The comprehensive indicator system considers the disaster system at multiple scales as a research subject and analyses the comprehensive impact of social, economic, technological, organisational, and other factors on the urban resilience system [20].

Considering the complexity of the factors affecting disaster resilience and the diversity of ways to enhance it, scholars often use a comprehensive evaluation method to evaluate urban disaster resilience and draw on technical methods of comprehensive indicator evaluation in specific research methods [21]. However, owing to limitations in data sources and evaluation technology systems, current research lacks a precise perception of the actual needs of residents for daily activities, making it impossible to include individual disaster-affected residents in the urban resilience research system [22]. At the same time, implementing the current research findings in high precision and large-scale geographic spaces is challenging, and it is difficult to balance research scale and accuracy [22].

This study considered the main urban area of Gaoyou City as a case study based on mobile internet technology, acutely observed the spatio-temporal activity trajectory and characteristics of residents, and selected haze disasters as the research object from numerous natural disasters that affect urban operations [23]. Haze disasters generally refer to the combination of fog and haze and are common in urban areas. Many regions in China combine fog with haze as a catastrophic weather phenomenon for early warning and forecasting, collectively referred to as haze disasters [21]. Haze is the result of the interaction between specific climatic conditions and human activities, and the economic and social activities of high-density populations inevitably emit a large amount of fine particulate matter [24]. Once the emissions exceed atmospheric circulation and carrying capacities, the concentration of fine particulate matter will continue to accumulate, and when the atmospheric environment remains in a static state, it is highly prone to large-scale haze disasters [24]. Urban haze disasters are characterised by wide coverage, high potential harm, high public attention, and difficult prevention and control [24,25]. The literature on haze disasters mainly focuses on the paradigm framework of 'Pattern-Mechanism-Effect', examining the governance mechanisms of urban disaster prevention from a regional level, and less on the monitoring and adjustment strategies of urban haze prevention and control from the perspective of urban resilience [26–28]. This study combined the existing research results and analysed the concept and connotations of disaster resilience from the perspective of resident activities. The interference of haze disasters on residents' daily lives, as well as the adaptive impact of built environments on residents' daily activities under haze disaster conditions, were examined. The comprehensive adaptive resilience to haze disasters in the main urban area of Gaoyou City was evaluated and corresponding resilience improvement strategies for the problem areas proposed. This study introduced the perspective of residential activities and systematically studied the impact of the built environment on the daily activities of residents in haze disaster environments. It integrated multi-element spatial data to quantitatively analyse the resilience value of haze disasters and constructed a feasible evaluation index system, providing a new and beneficial exploration for the study of urban disaster resilience.

2. Materials and Methods

2.1. Research Scope

Gaoyou is an important city in the eastern coastal region of China, adjacent to Gaoyou Lake and rich in natural resources, such as rivers, lakes, and water systems. Gaoyou City is a county-level city located in the central part of Jiangsu Province, with a total area of 1963 square kilometres [27]. In 2023, the permanent population of Gaoyou City was 709,600, consisting of 2 streets, 10 towns, and 1 township, with a total of 34 ethnic groups [27]. There are many industrial enterprises within the main urban area of Gaoyou, with a large amount of pollution discharge, especially high values of air pollutant emissions. The PM2.5 particle matter source analysis showed that industrial pollution was the main source of pollution, followed by motor vehicle exhaust emissions [29]. This article selected cross-sectional data from four years, 2014, 2017, 2020, and 2023, covering a period of approximately 10 years. In the past decade, the overall air quality in Gaoyou City has gradually improved, meeting the second-level standard for air quality for 238, 241, 252, and 256 days in four years, respectively [28]. The Air Quality Index (AQI) simplifies the concentration of several air pollutants commonly monitored into a single conceptual index value based on environmental air quality standards and the impact of various pollutants on human health, ecology, and the environment [29]. The main pollutants involved in air quality assessment are fine particulate matter, inhalable particulate matter, sulphur dioxide, nitrogen dioxide, ozone, carbon monoxide, and six other pollutants [29]. Among them, the second-level standard refers to an air pollution index of less than or equal to 100, indicating that the air quality has reached the excellent standard [30]. However, compared to similar cities, Gaoyou City still ranks relatively high in terms of air pollution levels among the key cities for environmental protection and control in China [30]. This study selected the main urban area of Gaoyou as the research object and collected the urban air pollution index based on air quality monitoring stations set up within the city (Figure 1).

The main urban area is the most densely populated, with modern service industries being the main industry type. There are few sources of air pollution in the area and most haze is imported from external areas [30]. Owing to the dense distribution of industrial enterprises near the northeastern side of the main urban area, the prevalence of northeastern winds in winter, and the relatively flat terrain of the main urban area, traditional haze control methods are ineffective [30]. Studies have shown that the effectiveness of unilaterally regulating haze pollution through industrial structure optimisation, environmental remediation, and other means is limited. In addition to strengthening regional joint prevention and control, it is necessary to comprehensively and systematically enhance the resilience of cities to cope with haze disasters throughout the entire process [7].

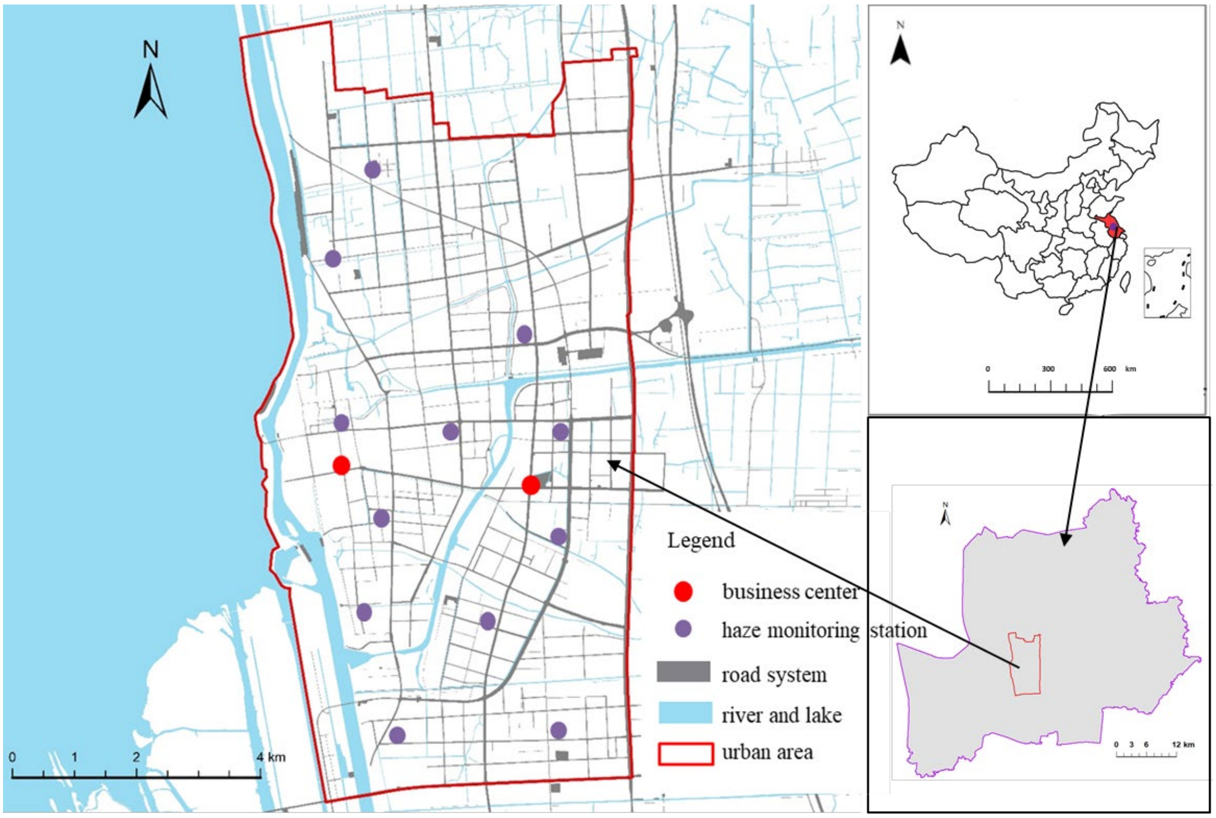


Figure 1. Location of Gaoyou and the study area.

2.2. Data Sources

This article conducted case studies in four years, 2014, 2017, 2020, and 2023, over a time span of approximately 10 years. We obtained specific air pollution data for four years, including socio-economic statistical yearbooks, the spatial data of various facilities in built environments, and mobile operator signalling data (Table 1). To unify the accuracy of the data analysis, we set the analysis unit of the study area as a 100 m × 100 m regular grid and the projection coordinate system as the Mercator WGS-1984 coordinate system. The data pre-processing included coordinate projection conversion and remote sensing image interpretation.

Table 1. Spatial data structure for evaluating urban haze disaster resilience.

Data Type	**Data Content**	**Data Volume (10,000 Pieces)**	**Period**	**Data Source**
Regional environmental data	Air quality monitoring station data per hour (AQI)	31.37	November and December of 2014, 2017, 2020, and 2023	Environmental Monitoring of China
	Landsat 8 satellite remote sensing image data (water coverage, forest coverage, vegetation coverage, etc.)	/	2014, 2017, 2020, and 2023	Chinese Academy of Sciences Geospatial Data Platform

Table 1. *Cont.*

Data Type	Data Content	Data Volume (10,000 Pieces)	Period	Data Source
Urban facility data	Baidu Map POI (bus stop, comprehensive hospital, fitness centre, supermarket, vegetable market, pharmacy, large shopping mall)	1.8	November and December of 2014, 2017, 2020, and 2023	Baidu Online Map Open Platform
	Urban road network (expressways, main roads, secondary roads, branch roads, bus stop lines)	0.8	2014, 2017, 2020, and 2023	
	Building foundation map	13.15	2014, 2017, 2020, and 2023	
Urban resident activity data	Population distribution heat point per hour	3251	November and December of 2014, 2017, 2020, and 2023	Mobile signalling data

2.3. Research Framework

The resilience index of urban haze disasters from the perspective of resident activities refers to the built environment's ability to absorb and avoid haze disasters when urban residents are exposed to them during their daily activities and the degree of interference to the normal quality of life and the health status of residents. Therefore, the resilience index of haze disasters can be quantitatively expressed as the ratio of the adaptability index of the built environment to haze and the interference index of haze on residential activities. Based on this, we constructed a resilience assessment index system for haze disasters, quantitatively measuring the demands of residents and the support capacity of the built environment for residents under haze disaster conditions. This was done to quantify the interference mechanism of haze on residents' activities and the adaptation mechanism of the built environment to haze.

Studies have suggested that the interference mechanism of haze on resident activities is influenced by various factors, including the necessity of daily activities, residents' perceptions of haze disasters, and their sensitivity to activities during haze disasters, which include direct impacts on resident activity spaces and indirect impacts on resident health [7]. Therefore, the interference of haze disasters on residents' activities has a comprehensive effect based on factors such as the severity of the haze, activity exposure, and activity sensitivity, which can be expressed as the sum of the three [31,32]. The ecological haze reduction index is an adaptation mechanism of the built environment to haze disasters and is achieved by ensuring the efficiency and health level of the daily travel activities of residents under haze disaster conditions [33]. The main approach is to absorb and dissolve haze-causing substances based on the physical and chemical effects of the ecological environment and to reduce the severity of the haze [34]. The haze avoidance index of facilities is used to reduce the probability of exposure and time that residents are exposed to the haze environment through a green travel environment, service-oriented living facilities, and medical service resources, and to weaken the degree of interference of haze disasters on residents' activities [35,36].

To determine resilience to haze disasters as the evaluation objective, determine the control and network layers, clarify the main influencing factors between indicators, and clarify the corresponding relationships between elements, we constructed a resilience assessment index system for haze disasters based on the network analysis method and obtained the weights of various non-independent indicators (Table 2). All indicators passed the consistency test (CR ≤ 0.1). Network analysis is a decision-making method proposed by Professor Saaty from the University of Pittsburgh in 1996, which is adapted to a non-independent hierarchical structure. It is a new practical decision-making method developed based on the Analytic Hierarchy Process [32]. Based on expert scoring, the network analysis method comprehensively evaluates the mutual influence between various factors at adjacent levels, uses matrix arrays to comprehensively score each group of factors, and obtains their mixed weights [32].

Table 2. Weight of evaluation indicators of urban haze disaster resilience.

First-Level Indicators	Indicator Weight	Second-Level Indicators	Indicator Weight	Third-Level Indicators	Indicator Weight
Disturbance to resident activities	0.57	Haze severity	0.38	The proportion of moderate and above haze weather	0.31
		Activity exposure	0.12	Probability of residents' outdoor activity exposure	0.15
		Activity sensitivity	0.07	Change rate of residents' activity intensity	0.06
Built environment adaptability	0.43	Ecological haze reduction effect	0.29	Vegetation coverage	0.22
				Water area density	0.07
		Facility haze avoidance effect	0.14	Accessibility of public transportation resources	0.11
				Accessibility of medical service facilities	0.04
				Accessibility of shopping and leisure resources	0.08

First-level indicators included the interference on residential activities and the adaptability of built environments. The interference of haze disasters on residential activities can only be reduced to a certain extent and will be difficult to completely eradicate. However, by improving the overall adaptability of the built environment, the resilience to urban haze disasters can be continuously enhanced. The weights of the secondary indicators were arranged in descending order and included five indicators: haze severity, ecological haze reduction, facility haze avoidance, activity exposure, and activity sensitivity. The third-level indicators were ranked in descending order of weight and included the proportion of haze weather in the past three years, vegetation coverage, probability of outdoor exposure to residential activities, accessibility of public transportation resources, water area density, rate of change in residential activities, and accessibility of shopping and leisure resources. Considering that the level of haze disasters is the most critical external interference source, it has a significant impact on the adaptability of residents and the carrying capacity of the built environment [37].

2.4. Research Methods

This study collected data from three aspects: the ecological environment, infrastructure, and resident activities. The network analysis method was used to analyse the network correlation between the indicators, and the entropy method was used to measure the factor weights of the non-independent indicators. Based on this, the model calculated the spatial distribution pattern and spatial topology relationship of resilience-related indicators for haze disasters, identified weak areas of urban resilience, and proposed targeted optimisation strategies. The research methods included the collection and analysis of spatial data, which mainly used self-designed web crawler programs and software. Specific analysis methods included accessibility and factor-correlation analyses.

(1) Facility accessibility analysis method

In terms of facility accessibility, this study measured the shortest-time accessibility of residents to public transportation facilities, life service facilities, and indoor health facilities under the condition of maximum travel probability [37]. Based on the accessibility index of urban facility resources at different levels, we subdivided resident transportation modes into walking and public transportation. Residents tended to choose public transportation when going to large public service facilities and walking when going to community convenience service facilities. Based on the walking speed of normal adults and the actual driving speed in the urban area of Gaoyou, this study set the walking speed to 4 km/h and public transportation speed to 30 km/h [38]. This study set the upper limit of the walking and driving range for residents based on a 15 min living circle walking-travel range and the 30 min actual commuting time in the urban area as indicator thresholds [39]. Large water bodies and green spaces without road connectivity are generally considered inaccessible [40]. The calculation method for the weights included two steps [41]. The weights of the facilities at different levels were determined by the ratio of the total amount of facility resources within the accessibility range to the total service population. The formula is as follows:

$$\mathrm{W} = \frac{SLR_n}{\sum_{i=1}^{n} SLR}, \; SLR = \frac{RQR}{PRA} \tag{1}$$

where W is the weight value of similar facility elements, SLR refers to the service capability of facility resources, RQR refers to the cumulative energy level of such facilities within the accessibility range, PRA refers to the total distribution of the permanent population within the accessibility range, and n refers to the number of similar resource types. Owing to the differences in the nature and interrelationships of the indicators, the weights of the different types of indicators can be obtained through network analysis. The network analysis method is a decision-making method proposed by Saaty that adapts to non-independent hierarchical structures [42]. This method constructs a structured self-loop analysis framework to simulate the correlations between real objects in a more reasonable way [43,44].

(2) Spearman correlation analysis

In statistics, the Spearman correlation coefficient analysis method does not have strict requirements for variable distribution, and its application scenarios are more extensive than those of the Pearson's correlation coefficient method. The rank coefficient can be applied to correlation analysis. However, this method is non-parametric, and its testing efficiency is lower than that of the Pearson's coefficient. The Spearman correlation analysis method has high accuracy in the correlation results between variables in practical applications, and simple steps can be used to calculate variable p. The formula is as follows:

$$r = \frac{\sum\limits_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum\limits_{i=1}^{n} (x_i - \overline{x})^2} \sqrt{\sum\limits_{i=1}^{n} (y_i - \overline{y}))^2}} \tag{2}$$

$$p = 1 - \frac{6\sum d_i^2}{n(n^2 - 1)} \tag{3}$$

The Spearman correlation coefficient indicates the direction of the correlation between independent variable x and dependent variable y. When x increases, y tends to increase, and the Spearman correlation coefficient is positive. As x increases, y tends to decrease, and the Spearman correlation coefficient is negative. A Spearman correlation coefficient of zero indicates that an increase in x does not have a directional effect on y. As x and y approach a completely monotonic correlation, the Spearman correlation coefficient increases in absolute value. When x and y are completely monotonically correlated, the absolute value of the Spearman correlation coefficient is 1.

(3) Binomial logistic regression analysis

Binomial logistic regression analysis is commonly used in public health and sociology research, which can comprehensively identify and test influencing factors. Binomial logistic regression belongs to probabilistic nonlinear models and is a multivariate analysis method for studying the relationship between built environment factors and residential activity exposure. The dependent variable Y follows a binomial distribution, with values of 0 and 1. The overall probability of $Y = 1$ is π $(Y = 1)$, and the m independent variables are X_1, X_2, $\cdots$ X_m, respectively. The binomial logistic regression model corresponding to the variable is:

$$\pi(Y = 1) = \frac{\exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_m x_m)}{1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_m x_m)} \tag{4}$$

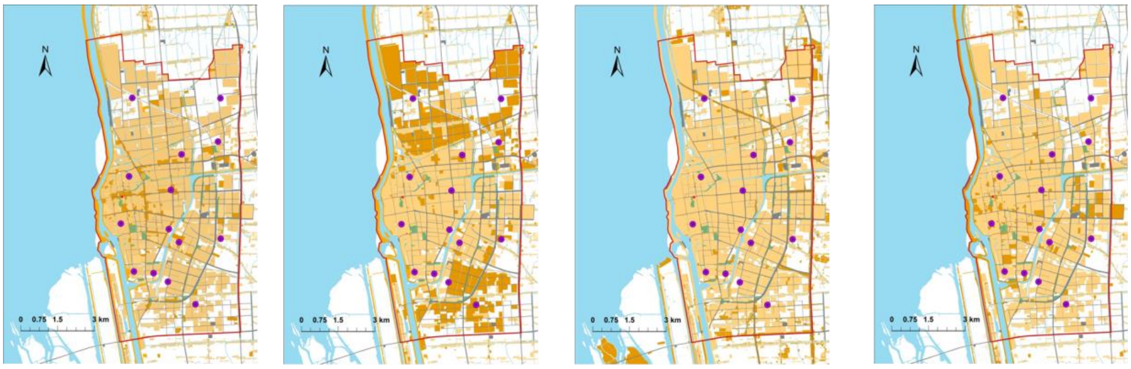
In the formula, x_1, x_2, …, x_m are the driving factors that affect the outdoor activity exposure of residents under haze disasters. β_0 means the intercept (or constant term). β_j means the regression coefficient corresponding to X_j (j = 1, 2,…, m). Positive (negative) values represent that the relevant independent variable $X_{j,\,i}$ can increase (decrease) the occurrence rate of event i. The larger the absolute β_j value is, the independent variable $X_{j,\,i}$ shows impacts on $X_{j,\,i}$ which have an occurrence rate of event i. Exp (.) is the index based on the natural logarithm [36]. Logistic regression can predict the probability of occurrence of each categorical variable. This model overcomes many limitations of multiple linear regression and does not assume a linear relationship between the dependent variable and the independent variable in advance, which can effectively address the problem of nonlinear effects in the model [37].

3. Results

3.1. The Spatial Feature of the Interference on Residential Activities in Haze Disasters

The resilience assessment of haze disasters included a comprehensive evaluation of the interference on residential activities, adaptability of built environments, and resilience to haze disasters. Key indicators were measured and divided into four levels–low, medium, high, and highest–using the natural discontinuity method. The overall level, spatial distribution pattern, and spatial topology relationship of the relevant indicators in the main urban area were analysed (Figure 2) to identify the distribution areas and characteristics of haze pollution. The results indicate that the disturbance of residential activities was most significantly affected by haze disasters, followed by the exposure index of residential activities. The sensitivity index had the smallest impact on the disturbance of residential activities. The average disturbance index of residents in the main urban area was 0.22, which is slightly lower than the average level. The mean values of the haze severity, activity exposure, and activity sensitivity indices were 0.271, 0.032, and 0.015, respectively, and the overall level was classified into three levels: medium, low, and low, respectively.

Under the comprehensive effects of haze severity, activity exposure, and activity sensitivity, the spatial distribution pattern of the resident activity interference index showed a multi-core circle-like clustering feature. Low-grade areas are mainly distributed in suburban parks, lakeside green spaces, both sides of rivers, and waterways around the urban area, as well as in the surrounding areas of urban sports squares. These areas have abundant ecological resources and fewer sources of haze pollution. High-level areas exist in the industrial area in the northern part of the urban area, the e-commerce area in the southern part, the area around garbage collection and incineration stations on the eastern side of the urban area, and the area on the east bank of Gaoyou Lake. These areas include both old urban blocks and open green spaces, such as sports parks. The scale of renovation, development, and construction in these areas is relatively large, with a large number of catering service formats on both sides of the main urban road. Emissions of oil fumes are high, and the degree of air pollution has significantly increased. Simultaneously, these areas have a dense distribution of residents, a high density of daily activities, and high traffic flow. Owing to the close correlation between air pollution exposure and residential activity agglomeration, industrial production spaces and residential living spaces are the main areas for daily activities. Residents frequently commute to and from these areas, resulting in relatively high environmental exposure and low sensitivity to haze disasters [45].



Exposure to resident activities Sensitivity to resident activities Ecological haze reduction capacity Facility anti haze capability

The severity of haze pollution The degree of disturbance to resident activities Adaptability to Built Environment Urban resilience in response to haze disasters

Figure 2. Evaluation of resilience indicators for urban haze disaster response.

3.2. The Spatial Feature of the Adaptability of the Built Environment in Haze Disasters

Under the comprehensive influence of ecological haze reduction and facility haze avoidance indicators, areas with high environmental adaptability indices are mainly distributed along the main and secondary road networks of the cities, exhibiting significant spatial agglomeration characteristics in a belt shape. The average adaptability index of the built environment in the main urban area was 0.103, indicating a moderate overall level. The mean values of the ecological haze reduction index and facility haze avoidance index were 0.041 and 0.057, respectively, with scores at the lower and medium levels. The facility haze avoidance index had a greater impact on the environmental adaptability index of the built-up areas. The spatial distribution range of the ecological haze reduction index is consistent with the overall ecological pattern of the urban area. Winter is a period of frequent haze disasters. Owing to the sharp drop in temperature, urban water areas and vegetation coverage will also undergo significant changes [46]. Differences in vegetation types also led to changes in the green space coverage index within the city. However, owing to differences in the size and effectiveness of green spaces in reducing haze, large urban ecological green spaces can effectively enhance the ecological haze reduction index. The haze avoidance index of facilities was significantly influenced by the accessibility index of bus stops, and areas above average formed a banded distribution feature, with bus stops as nodes and continuous spatial continuity. Meanwhile, the distribution characteristics of indicators, such as accessibility to bus stops, entertainment facilities, and medical facilities, were significantly stratified. Studies have also suggested that public transportation has advantages, such as low carbon emissions and high timeliness, which have a positive impact on the convenience of residents in shopping, entertainment, and daily travel. It also reduces the interference of haze disasters on residents' daily activities from multiple aspects, such as haze severity, activity exposure, and activity sensitivity [47].

3.3. There Is a Significant Correlation between the Built Environment and Residential Activity in Haze Environments

This article obtained the spatial location of the hourly urban residents' distribution through mobile signalling data. At the same time, we mapped the location of residential activity spaces to the physical spatial elements of the built environment, determined whether the activity venues of residents were in indoor or outdoor spaces, and defined outdoor activities as residential activity exposure, calculating the ratio of residential activity exposure to the overall activity scale of residents. We measured the Spearman correlation index between the residential activity and built environment indicators. The results showed that the correlations between the severity index of haze, the sensitivity index of residential activities, and the ecological haze reduction index in the built environment were 0.781 and 0.932, respectively, and were significantly correlated at the 0.01 level (bilateral). The correlation between the residential activity exposure index and ecological haze reduction index was very low (0.320), and there was no significant correlation. The results indicate that there is a significant correlation between the severity of haze disasters, the sensitivity of residential activities, and the level of ecological haze reduction in the built environment. However, the correlation between residential activity exposure and the level of ecological haze reduction in built environments was not significant (Table 3).

Table 3. The correlation between ecological haze reduction indicators and residential activity indicators in the built environments.

Indicator Analysis Item	**Haze Severity**	**Resident Activity Sensitivity**	**Resident Activity Exposure**
Spearman correlation analysis between ecological haze reduction and resident activity levels	0.781 *	0.932 **	0.320
Significance level (bilateral)	0.000	0.001	≥0.05 (not significant)
Sample quantity N	2112	2112	2112

Note: ** Significant correlation at the 0.01 level (bilateral); * significant correlation at the 0.05 level (bilateral).

The correlation analysis results show that there is a significant correlation between the severity of urban haze, the sensitivity of residential activities, and the level of ecological haze reduction in the built environment. However, there was no significant correlation between residential activity and the level of ecological haze reduction. The results indicate that in haze-polluted environments, residents often do not deliberately change their daily activity venues and travel patterns and, therefore, make corresponding adjustments in terms of travel frequency and the duration of outdoor activities. From the correlation results of facility haze avoidance indicators, it can be seen that the correlation between resident exposure sensitivity, resident activity sensitivity, and facility haze avoidance indicators in the built environment are 0.974 and 0.632, respectively, and are significantly correlated at the 0.01 level (bilateral). The correlation between the haze severity index and facility haze avoidance index was very low (0.281), and there was no significant correlation. The results indicate that there is a significant correlation between residents' exposure sensitivity, activity sensitivity, and the level of facility haze avoidance in the built environment, whereas the correlation between haze severity indicators and the level of ecological haze reduction in the built environment was not significant (Table 4).

Table 4. The correlation between facility haze avoidance indicators and residential activity indicators in built environments.

Indicator Analysis Item	**Haze Severity**	**Resident Activity Sensitivity**	**Resident Activity Exposure**
Spearman correlation analysis between facility haze avoidance and resident activity levels	0.281	0.632 **	0.974 **
Significance level (bilateral)	≥0.05 (not significant)	0.001	0.000
Sample quantity N	2112	2112	2112

Note: ** Significant correlation at the 0.01 level (bilateral).

The correlation analysis results between resident activity exposure and built environmental factors in different years under the control of the air pollution index are shown in Table 5. The analysis results of some models are consistent with the conclusions of the descriptive statistical analysis in Tables 3 and 4. First, there is a significant correlation between vegetation coverage indicators, accessibility indicators of public transportation facilities, and residential activity exposure. Compared to the results in 2014, the vegetation coverage indicators in 2020 and 2023 showed a more significant positive correlation with the outdoor activity exposure of residents, while the accessibility indicators of public transportation facilities showed a significant negative correlation with the outdoor activity exposure of residents. This conclusion is similar to the research results published by existing scholars [38]. This study investigates the relationship between the built environment and the outdoor activities of residents in haze environments, and the results show that public green space has a significant impact on walking activities, followed by buses and subways, and private cars have the lowest impact. In addition, the indicators of water area, accessibility of medical facilities, and accessibility of shopping and leisure facilities in urban areas show a significant correlation with the exposure of residents to outdoor activities in individual years. This conclusion is similar to the existing research findings, which suggest that the density and accessibility of leisure facilities such as healthcare, catering, and shopping can directly affect residents' willingness to go out and change the frequency and intensity of outdoor activities [42].

Table 5. The correlation analysis between resident activity exposure and built environment factors in different years under a haze disaster environment.

		Vegetation Coverage Rate	**Water Area**	**Accessibility of Public Transportation Facilities**	**Accessibility of Medical Facilities**	**Accessibility of Shopping and Leisure Facilities**
Resident activity exposure (2014)	Spearman correlation	0.706	0.671	−0.412	−0.237	0.306
	Significance (double-tailed)	0.102 *	0.089 **	0.752 *	0.267 **	0.734 *
	Covariance	0.031	0.497	−0.031	−0.089	0.072
Resident activity exposure (2017)	Spearman correlation	0.713	0.618	−0.552	−0.589	0.514
	Significance (double-tailed)	0.382 *	0.352 **	0.304 **	0.076 *	0.717 *
	Covariance	0.056	0.017	0.013	0.073	−0.025
Resident activity exposure (2020)	Spearman correlation	0.119	0.093	−0.105	−0.002	0.091
	Significance (double-tailed)	0.728 **	0.231	0.181 **	0.718	0.231 *
	Covariance	0.049	0.431	0.120	0.035	0.367
Resident activity exposure (2023)	Spearman correlation	0.189	0.531	−0.131	−0.078	0.056
	Significance (double-tailed)	0.632 **	0.338	0.126 **	0.849 *	0.217
	Covariance	0.082	0.421	0.157	0.027	0.356

Note: *, ** respectively represent $p = 0.1$, $p = 0.05$.

3.4. The Urban Resilience Index Characteristics in Haze Disasters

The average resilience index for haze disasters in the Gaoyou urban area was 0.412, which is moderate to low. The interference indices of residential activities and the built environment adaptability were 0.236 and 0.092, respectively, both at a moderate to low level, indicating that the interference on residential activities had a relatively greater impact on resilience to haze disasters. From the perspective of spatial distribution characteristics, the spatial differentiation of the resilience index for urban responses to haze disasters is not obvious, and the resilience values of lower levels of haze disasters occupy the vast majority of regions. The urban resilience indices of Gaoyou City's large green squares, high-speed rail hub stations, and areas surrounding major rivers were relatively high. Large public buildings and green spaces have strong anti-haze effects that can alleviate the interference of haze on residential activities. Due to the concentrated distribution of areas with good adaptability of built environments, the distribution areas of high-grade facilities are relatively concentrated. However, there was a mismatch between the spatial distribution areas of the facility carrying capacity index and the resident activity interference index, and the degree of spatial matching was not high. American scholars conducted a tracking study on the resilience index of infrastructure in major cities such as Chicago. They found that, under disaster weather conditions such as high temperatures, heavy snow, and haze, areas with well-developed infrastructure have a higher comprehensive resilience index, and residents have a lower probability of being affected by disasters and less interference in their daily activities [46,47].

4. Discussion

4.1. Differentiated Effects of Different Built Environment Characteristics on Residential Activities in Haze Environments

From the correlation structure system of the resilience indicators for urban haze disasters, it can be observed that a good ecological environment has good adsorption, degradation, and transformation functions for urban haze (Figure 3). Natural ecological environments are the main spaces for residents' outdoor activities. The distribution density of urban ecological resources can effectively reduce the exposure and sensitivity of residents to outdoor activities, with vegetation having a greater haze reduction effect than water bodies. The haze avoidance index of facilities refers to the accessibility index of residents for public transportation, medical services, shopping, and leisure resources. Facilities reduce the exposure and sensitivity of residents' activities by providing daily travel safety, fitness activities, shopping, and entertainment space needs [46]. Specifically, public transportation accessibility has a significant promoting effect on the accessibility of medical service facilities, shopping, and leisure resources. At the same time, public transportation meets the policy requirements of low-carbon travel for residents and has a positive effect on urban haze reduction. Considering the differences in the frequency of daily activities and modes of travel among residents, the importance of accessibility to public transportation, entertainment facilities, and medical services has gradually decreased. The activity exposure index reflects the intensity of the residents' outdoor activities. Residents exposed to haze during outdoor activities experience adverse effects on their physical and mental health, travel safety, and convenience of life, and also have negative effects on haze reduction [47]. The external environment is the spatial location where the haze affects residents' activities. Although there is a feedback mechanism for the sensitivity of activities to exposure and the severity of haze, the index generally only accepts the one-way impact of built environment adaptability indicators [47].

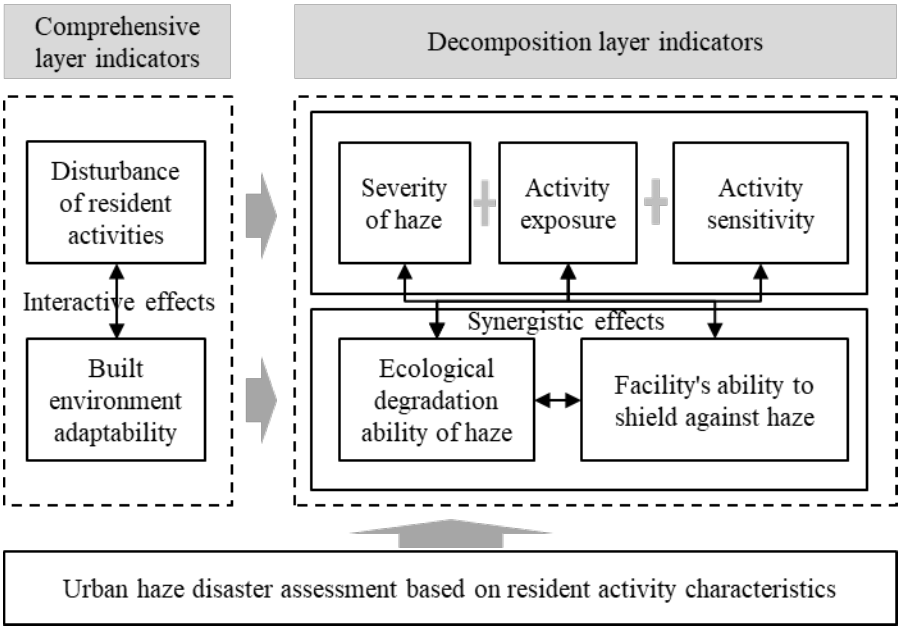


Figure 3. The correlation structure system of resilience indicators for urban haze disasters.

According to the results in Table 6, under a high-concentration air pollution environment, the impact of natural resource elements and public service facilities on the outdoor activity exposure of residents in the Gaoyou urban area is more significant. Residents are more susceptible to the influence of haze factors when engaging in outdoor activities in high-concentration haze environments. Studies have shown that residents who choose different modes of transportation from their place of residence to medical and shopping facilities experience significant differences in their exposure to haze [40]. Under high concentrations of haze pollution, residents prefer to take public transportation to reach their destination. The accessibility indicators of public service facilities such as public transportation, medical facilities, shopping, and entertainment facilities are significantly negatively correlated with residents' outdoor exposure [47].

Table 6. The regression model of the impact of the built environment on residents' exposure to outdoor activities.

Influence Factor	**Vegetation Coverage Rate**		**Water Area**		**Accessibility of Public Transportation Facilities**		**Accessibility of Medical Facilities**	**Accessibility of Shopping and Leisure Facilities**		
	Sig.	**Exp(B)**	**Sig.**	**Exp(B)**	**Sig.**	**Exp(B)**	**Sig.**	**Exp(B)**	**Sig.**	**Exp(B)**
Air Quality Index (control: $150 < AQI \leq 200$)	0.726	/	0.823	/	0.915	/	0.931	/	0.904	/
$AQI \leq 50$	0.823	0.811	0.736	0.041	0.982	0.032	0.917	0.981	0.986	0.981
$50 < AQI \leq 100$	0.753 *	1.274	0.891 *	0.071	0.968 **	0.055	0.801 **	1.285	0.801 *	1.285
$100 < AQI \leq 150$	0.676 **	0.634	0.912	0.037	0.999	0.051	0.659 *	0.649	0.659 **	0.649
Resident activity exposure (control: 2014)	0.795	/	0.801	/	0.060	/	−0.731	/	−0.882	/
Exposure index for 2017	0.918 *	0.911	0.607	2.227	0.735 *	0.609	−0.931 *	0.923	−0.841 *	0.723
Exposure index for 2020	0.837 **	1.156	0.834 *	1.247	−1.242 **	1.335	−0.833	1.089	−0.772 *	1.117
Exposure index for 2023	0.178	0.465	0.432 *	2.014	−0.137	1.524	−0.128 **	0.433	−0.191	0.512
Constant	0.999	3.732×10^8	0.993	3.983×10^2	0.972	1.281×10^2	0.931	3.781×10^2	0.764	2.331×10^2
Sample size	1892		791		526		72		69	
Log-likelihood	236.670		103.435		89.087		67.172		55.920	
Cox and Snell R^2	0.141		0.115		0.193		0.92		0.913	
Nagelkerke R^2	0.173		0.231		0.382		0.112		0.781	

Note: *, ** represent $p = 0.1$, $p = 0.05$, respectively.

Meanwhile, compared to 2014, the exposure of residents to outdoor activities in 2017 and 2020 was more significantly affected by the urban built environment. With the rapid urbanisation process in China, the urban built environment has significantly improved in the past decade, and the construction of various public service facilities and open activity spaces has improved. Improved landscape green space facilities and public transportation service facilities can help residents more conveniently access resource elements, thereby reducing the exposure of residents to haze during long-term transportation [47]. However, in high-density residential areas of cities, building additional dense green square spaces and green public transportation facilities can help to sequester carbon and reduce environmental temperature, as well as effectively reduce the exposure risk of residents going out for activities.

4.2. Improve the Matching Degree between Residential Activity Spaces and Green Square Facilities

This study identified the spatial distribution pattern and influencing factors of resilience to haze disasters and proposed differentiated response measures to reduce the interference of haze pollution on residential activities in areas with high levels of activity interference and low adaptability of built environments. This would help improve the adaptability of built environments to resist haze disasters. The haze severity index, activity exposure index, and activity sensitivity index in the main urban area have a comprehensive impact on residents' activities. However, the ecological haze reduction and facility haze avoidance indices have comprehensive impacts on the adaptability level of the built environment. For areas with low resilience to haze disasters, it is necessary to improve the degree of matching between large-scale green space facilities and the main activity areas of residents in terms of spatial pattern distribution, and to improve the accuracy and efficiency of the built environment resilience index. Specifically, in dealing with the interference of haze on residents' daily activities, reducing the level of haze pollution should focus on controlling pollution sources, such as automobile exhaust emissions, construction dust, and catering fumes. Reducing the level of activity exposure should avoid excessive population aggregation, reasonably allocate populations, increase the number of indoor activity venues, and pay special attention to the effective guidance and diversion of the population in old urban areas.

4.3. Improve the Density and Quality of Public Transportation Facilities in Built-Up Areas

In terms of building environmental adaptability, enhancing the ecological haze reduction capability of urban spaces, improving the layout and quality of urban ecological spaces, and achieving a more balanced distribution of construction spaces in the old urban area and its surrounding areas in the west and north are recommended. The proportional structure of the construction and ecological spaces should be more reasonable. Strengthening the construction of ecological green spaces around old streets in urban areas can effectively reduce the impact of haze disasters. In addition, reducing the activity sensitivity index enhanced residents' perceptions of haze and strengthened their self-protection abilities against haze pollution. Finally, in old urban communities and densely populated areas, it is recommended to increase the density and quality of public transportation service facilities; increase the coverage of public transportation, especially bus stops; promote green and low-carbon modes of transportation, especially in the northern, northeastern, and southeastern areas of the main urban area; and develop more public transportation platforms, as well as open more transportation operation routes.

In terms of building environmental adaptability, it is recommended that different measures be implemented to prevent and control haze. Pollution source control should be implemented to reduce the severity of haze disasters in the northern and northeastern regions of the main urban areas. Simultaneously, we should strengthen the integrated construction of public transportation facilities and improve their haze avoidance indices. For the northern and southeastern regions of the main city, where the level of infrastructure construction is relatively high, controlling the sources of pollution and reducing the severity of the haze are recommended. For the southern part of the main city with a high population density, it is recommended to control personal travel activities, disperse the population activity density, and reduce the impact of haze pollution on residents' health [47].

5. Conclusions

5.1. Key Findings

This study identified the spatio-temporal characteristics of the daily behavioural activities of residents in a haze environment, evaluated the resilience level of cities to cope with haze disasters, and analysed the actual interference level of haze weather on residents' activities, the support and adaptation ability of the built environment on residents' activities, and their interaction relationship. This study constructed a resilience index system for haze disasters, classified and set the weights of relevant indicators, evaluated the spatial distribution pattern of resilience in urban areas to cope with haze disasters, and arrived at the following main conclusions.

(1) Interference with residential activities and the adaptability of built environments are key indicators for evaluating urban resilience in haze environments, with weights of 0.57 and 0.43, and correlation indices of 0.671 and 0.812, respectively. The overall scores of the interference index, built environment adaptability index, and haze disaster resilience index of urban residents show a moderate to low level. At present, the adaptive construction of built environments in urban areas has an insufficient effect on improving haze disaster resilience.

(2) From the perspective of spatial distribution characteristics, the spatial characteristics of the disturbance index of residential activities and the built environment adaptability

index show a multi-core circle-like clustering and a 'belt like' clustering distribution along roads, respectively. The spatial mismatch between the two results in a lack of significant spatial differentiation in the resilience value of cities coping with haze disasters, and the resilience value of most urban areas is relatively low.

(3) The exposure index of residential activities is significantly influenced by the indicators of built environment factors, among which the vegetation coverage index shows a significant positive correlation (0.837), and the accessibility index of public transportation facilities shows a significant negative correlation (-1.242). In addition, compared to 2014, the impact of built environmental factors on the resident activity exposure index was more significant in 2017 and 2020. The results indicate that improved landscaped green space facilities and public transportation service facilities can help residents more conveniently access resource elements and reduce their exposure to haze environments.

5.2. Implications

This study used spatial facility distribution and resident activity data to analyse the spatial characteristics of the haze disaster resilience index in various urban areas. This study focused on analysing the degree of spatial matching between residential behaviour and infrastructure in haze environments, evaluating a comprehensive index of urban haze resilience, identifying the main difficulties and problems in controlling haze pollution in different regions, and proposing targeted optimisation control strategies for urban haze pollution prevention and control. Compared to existing engineering- and management-based urban resilience evaluation methods, this study proposed an urban resilience evaluation and response strategy from the perspective of resident activities guided by resident needs, carrying out facility layout and matching and proposing response strategies and paths. The research results provide a reference for subsequent urban spatial governance and resilient city construction [37,42].

5.3. Limitations and Future Research Directions

This study began from the perspective of the daily activities of residents, identified the carrying capacity and support of various urban infrastructures for residents in a haze disaster environment, and comprehensively evaluated the urban resilience index. Compared with the existing research on the urban resilience index in the engineering field, this study focused on a smaller scale and emphasised the matching degree between urban facility supply and resident activities, emphasising the residents' perception effect on the urban resilience index. This study expanded the traditional research perspective on disaster resilience, starting from the impact of disasters on residents' daily activities, and clarified a strategic path for enhancing resilience. This study was based on the fusion analysis of multiple spatial data, expanding the application fields of geospatial data and introducing resident behaviour data into the study of urban resilience spatial evaluation. However, owing to limitations in the data sources, this study mainly focused on the evaluation of the static spatial resilience index, with less consideration given to the mobility of haze air and the actual trajectory of residential activities. The resilience assessment of haze disasters based on mobile spaces should be the next direction of in-depth research.

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