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Assessment of urban flood resilience based on the socio-ecological composite index model: a case study in Wuhua District, Kunming City, China

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ABSTRACT

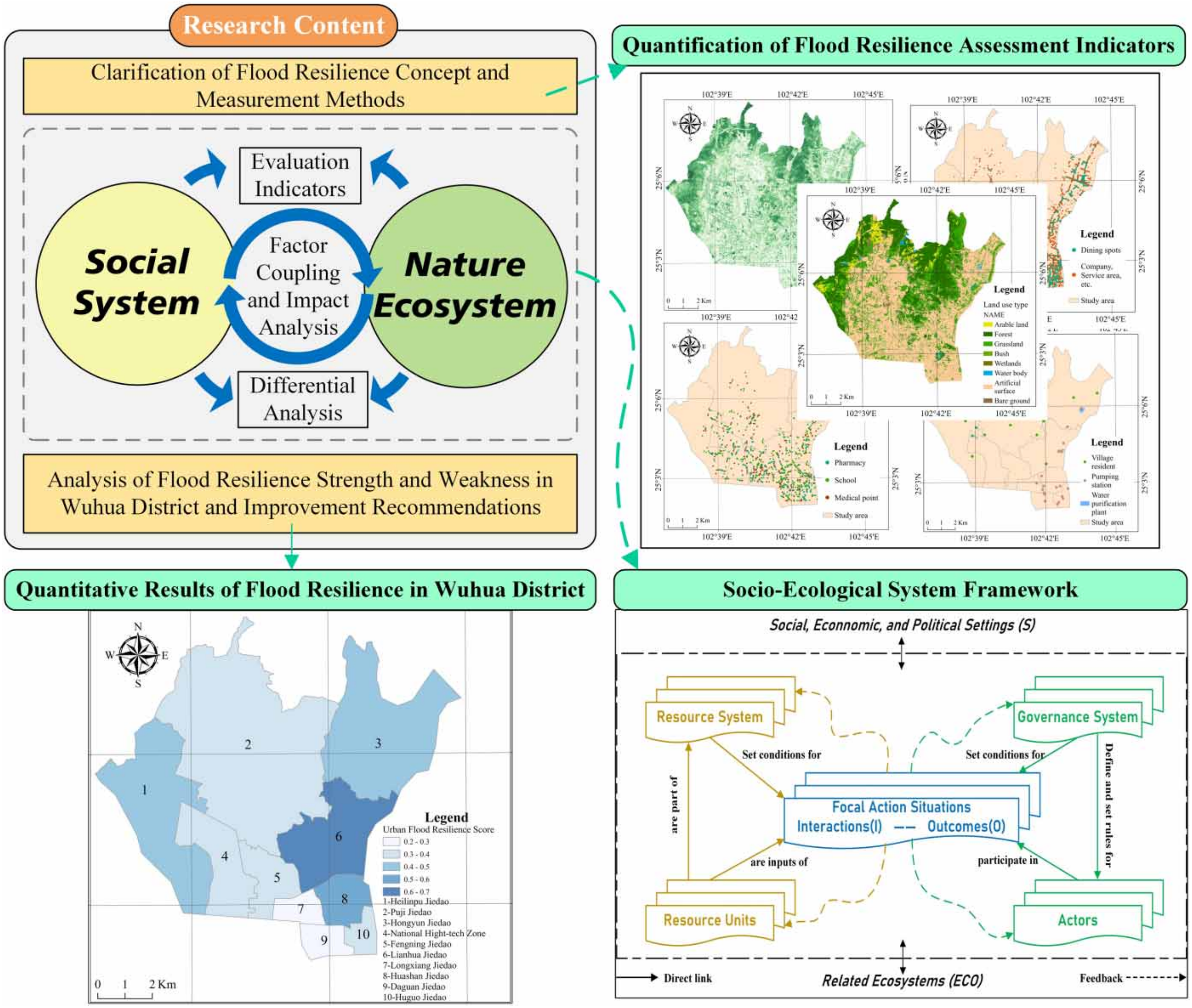
Global climate change and rapid urbanization have increased the frequency of flooding, making urban flood resilience a critical objective. This article introduces a methodology for assessing urban flood resilience, utilizing a social-ecological synthesis index that integrates geographical and temporal data with Geographic Information System (GIS). The study focuses on ten administrative subdistricts in Wuhua District, Kunming City, China, and selects 18 social-ecological indicators. These indicators, chosen from social and ecological perspectives, are weighted using the entropy weight method to determine their significance in the assessment system. By combining scores for each subdistrict, the study quantifies flood resilience and creates a spatial distribution map using ArcGIS. Key findings reveal that out of the ten administrative subdistricts, five in Wuhua District, particularly in the core urban area of Kunming, demonstrate strong overall flood resilience. Influenced by social-ecological indicators, there is significant spatial differentiation in flood resilience within Wuhua District, with a decreasing trend radiating from the city center to areas farther from the urban core. The research indicates that regions with well-established transportation infrastructure, a wide distribution of government institutions, improved water management facilities, and a substantial population with higher education levels contribute significantly to enhancing urban flood resilience.

Key words: entropy weight method, flood resilience, GIS analysis, spatiotemporal analysis, weighting indicators

HIGHLIGHTS

- Analyzing urban flood resistance capacity from the perspective of resilience.
- Considering the performance of both social and ecological dimensions in urban flood resilience.
- Quantifying urban flood resilience through comprehensive index method.
- Using geographic information technology to analyse the spatial characteristics of urban flood resilience.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The prevalence of extreme weather events and the rapid expansion of urban areas have increased societal vulnerability in the context of global climate change (Kotzee & Reyers 2016). This phenomenon has resulted in a rise in the frequency and severity of urban rainstorms due to climate change. Urban flooding, as a persistent issue, has now become a recurring occurrence that cannot be promptly eradicated, making it a prominent indicator of urban safety concerns. Over the past decade, China has incurred annual losses of 300 billion yuan (Sun & Yao 2019) due to climate change. Consequently, the examination of cities' capacity to withstand flooding has become a central focus in the current research (Bibi *et al.* 2023). A city, as a comprehensive system composed of multiple social-ecological subsystems, is continuously exposed to various external influences and disruptions, both from the external environment and within the system itself, during interactions with the outside world. These disturbances are caused by objective laws of social and natural development and cannot be completely avoided (Shao & Xu 2015). For example, in July 2016, heavy rains fell in Handan County, Hebei Province, causing severe floods. The county's seven townships (towns) and two parks were all affected to varying degrees (Shi *et al.* 2016). The torrential rainfall on 20 July 2021, in Zhengzhou, Henan Province, led to catastrophic floods, impacting all seven townships and two parks within the county to differing extents. The disaster killed and disappeared 380 people, and the direct economic loss was 40.9 billion yuan (Zhang *et al.* 2022). The June 2022 flood in southern China caused massive social and economic losses.

The severe flooding disaster that occurred in the Beijing–Tianjin–Hebei region of China in August 2023, triggered by Super Typhoon Doksuri, resulted in significant loss of both human lives and property. These extreme disaster events clearly underscore the inadequacy of traditional urban flood control management strategies in the face of global climate change. It is imperative that we expeditiously construct resilient cities capable of predicting, withstanding, and swiftly recovering from natural disasters to mitigate the losses incurred. Consequently, the measurement and quantitative expression of cities' recovery capabilities in flood disaster scenarios have emerged as a pressing scientific concern necessitating further research (Bibi 2022; Bibi & Kara 2023).

The term 'resilience,' derived from the Latin word 'resilio,' means 'rebound,' and it is defined as the return of a thing to its original state after being disturbed by the outside world (Klein *et al.* 2004). In the 1970s, ecologist Holling pioneered the description of multiple equilibrium states in natural systems and introduced the concept of resilience to depict a system's capacity to absorb diverse changes (Holling 1973). Over time, as people's comprehension of systems theory has deepened, the connotation of resilience has continued to evolve and refine itself. The Resilience Alliance defines a resilient city as a city or urban system's ability to digest and absorb external disturbances while retaining its original main features, structures, and key functions. It summarizes and constructs a framework for researching resilient cities (Resilience 2007). From the standpoint of urban management, Johansen *et al.* (2016) introduced the concept of the urban resilience index, asserting that urban resilience hinges on assets, policies, social capital, and institutions. This index serves as the initial tool for evaluating urban resilience. In addition, Cutter *et al.* (2010) formulated a community baseline resilience assessment index system that dissects urban resilience into six components: social resilience, economic resilience, community resilience, institutional resilience, infrastructure resilience, and ecological resilience. This framework allows for the quantification and analysis of resilience levels across distinct regions, thereby revealing spatial variations. Allenby & Fink (2005) investigated social system stability and concluded that improving urban community security systems can improve social resilience. In a comprehensive review of theoretical literature, Masnavi *et al.* (2019) applied the principles of resilience thinking to the field of urban research. Their work focused on identifying the foundational elements essential for future studies in the realm of urban resilience. In addition, Chen *et al.* (2017) expounded upon the conceptual facets of resilient cities and consolidated the planning requisites for such cities, encompassing economic, engineering, ecological, and societal considerations, within the context of resilient city development. It is important to note that there is currently no universally accepted definition of urban resilience. The exploration of urban flood resilience, which is rooted in the broader concept of urban resilience, is an ongoing area of investigation. Nevertheless, the recurrence of flood disasters induced by frequent extreme weather events poses substantial risks to both the safety of individuals and the security of their property. Consequently, it is of utmost urgency to delve into the assessment of urban flood resilience to tailor and implement effective flood protection strategies for urban areas.

Urban flood resilience is the capacity of urban systems to adapt to and recover from floods with reduced damage. This entails city design that allows for coexistence with floods by mitigating risks and potential damage (Miguez & Veról 2017). In this context, various studies have explored and developed methodologies for assessing urban flood resilience. Oladokun & Montz (2019) employed the definition of resilience from the National Academy of Sciences of the United States to create a conceptual and mathematical model, implementing fuzzy logic to generate resilience indices for three flood-prone communities in the United States. Tayyab *et al.* (2021) evaluated the urban flood control capacity of Peshawar, Pakistan, using ArcGIS, remote sensing, the analytical hierarchy process (AHP), and the urban flood resilience index. They introduced a comprehensive urban flood control model, incorporating multiple index parameters, including flood hazard, exposure, sensitivity, and coping capacity, achieving an accuracy rate of 90.4% in urban flood resilience assessment results. Wang *et al.* (2019) utilized the CADDIES model, based on two-dimensional cellular automata, to simulate urban surface flooding. Wang *et al.* (2017) developed an urban rainstorm and waterlogging disaster risk index evaluation model using the spatial analysis module 'Model builder' in ArcGIS and spatial modeling technology. He *et al.* (2022) applied the mandatory determination method, entropy value method, and spatial autocorrelation analysis to examine the spatiotemporal evolution characteristics of flood disaster resilience in 27 cities in the Yangtze River Delta from 2008 to 2018. Their analysis covered the dimensions of society, economy, infrastructure, and the environment. Bulti *et al.* (2019) investigated existing tools for assessing community flood resilience, with a focus on methods that account for the multifaceted nature of resilience. Their findings suggest that current community flood resilience assessment frameworks do not adequately address the multifaceted aspects of resilience, resulting in inconsistencies in measuring community flood resilience.

The formulation of an evaluation index system holds paramount significance within the framework of flood resilience assessment. The selection of indicators, their representativeness, completeness, and scientific rigor, can influence the results of flood resilience evaluation to a certain extent. The establishment of a robust theoretical underpinning serves as the bedrock for the development of primary indicators (Burton 2012; Chelleri 2012). Moreover, the identification of the most appropriate indicators to accurately depict the flood disaster resilience mechanism and its developmental trajectory is a critical consideration. Some argue that building resilience is a dynamic process, thus emphasizing the necessity for assessment frameworks to encompass both static and dynamic aspects (Bruneau *et al.* 2003; Rutter 2012; Johnson & Blackburn 2014). Nevertheless, it is noteworthy that the majority of existing measurement methods perceive resilience as either an outcome or a process.

At present, for resilient cities, to develop the framework for modeling the urban ecosystem from the perspective of single-cell ecology and engineering, the strengths, weaknesses, and components of urban disaster resilience in different contexts have been studied, focusing on the disaster threat posed by extreme weather events to cities at a social level. Research on multiple dimensions of urban resilience, including social, ecological, economic, and government guidance and decision-making, should be carried out.

This study investigates flood resilience, focusing on comprehending and overseeing the capability of socioecological systems to adjust to, react to, and recuperate from unforeseen calamities. It also explores possible efficient approaches to confront these disasters. In a socio-ecological system equipped with flood resilience, the ability to manage flooding disruptions offers dependable assurance for cities in pursuing sustainable development amid changing environmental conditions. There is a serious lack of sufficient data and uncertain model results, which makes the measurement of urban resilience difficult due to complex interactions between societies and ecosystems (Wang *et al.* 2020), nonlinear feedbacks, spatial and temporal changes, and practical issues; therefore, it is necessary to research to find a computationally simple and transparent way to measure the flood resilience of social-ecological systems in the face of flooding. The current mainstream urban flood resilience analysis methods include the social-ecological composite index method, single-index model, the AHP, and structural equation modeling. These methods determine the factors affecting urban flood resilience from the quantitative, qualitative, and first qualitative and then quantitative perspectives (Chen *et al.* 2020). Among them, the social-ecological composite index method, as a new resilience research method, combines the advantages of the aforementioned methods and also effectively solves the problem of the accuracy of the urban flood resilience model in the complex situation between the society and the ecological system.

Based on previous studies on urban resilience, in this article, urban flood resilience is defined as the capacity of urban systems to respond in advance in the face of shocks like flooding, the hard power of the city to resist disasters such as floods, the resilience of various systems in the city after the disaster, and the ability of the city to reflect and deal with flood disasters; therefore, it is concluded that the resilience is composed of four indicators. It is crucial to highlight that the existing urban flood resilience is notably shaped by social and ecological factors. Within the scope of this study, social factors comprise the examination of drainage systems, population demographics, and economic metrics. Meanwhile, ecological factors involve the evaluation of natural environments and land use conditions, alongside other relevant indicators. The amalgamation of these two sets of factors, along with their respective indicators, serves as the foundational framework for a comprehensive quantitative assessment and research of urban flood resilience. As a result, this article's objective is to employ spatiotemporal data and GIS techniques to establish a flood resilience assessment methodology grounded in a social-ecological composite index model (Figure 1).

This article focuses on Wuhua District in Yunnan Province, China, as the research subject. The study establishes an evaluation system for the urban flood resilience model in the area, considering geographical conditions and the social and ecological environment of Wuhua District. The research outcomes offer a practical foundation for decision-making in relevant departments. The study objectives include:

(1) Creation of an urban flood resilience evaluation model using the socio-ecological composite index method: by considering factors such as social, economic, ecological, and policy aspects, and employing the entropy weight method to determine the weight values of these factors, an urban flood resilience evaluation model is developed.
(2) Assessment of flood resilience in administrative subdistricts within Wuhua District and the creation of a horizontal spatial distribution map for flood resilience: the urban flood resilience evaluation model is applied to assess flood resilience in the cities under study, and a spatial distribution map illustrating the varying levels of flood resilience in different areas of Wuhua District is generated by combining GIS-based spatial analysis functionality.
(3) Quantitative GIS-based assessment of flood resilience: the ArcGIS mapping function was used to complete the distribution map of the flood resilience index in the study area, analyze the results of the evaluation of flood resilience in

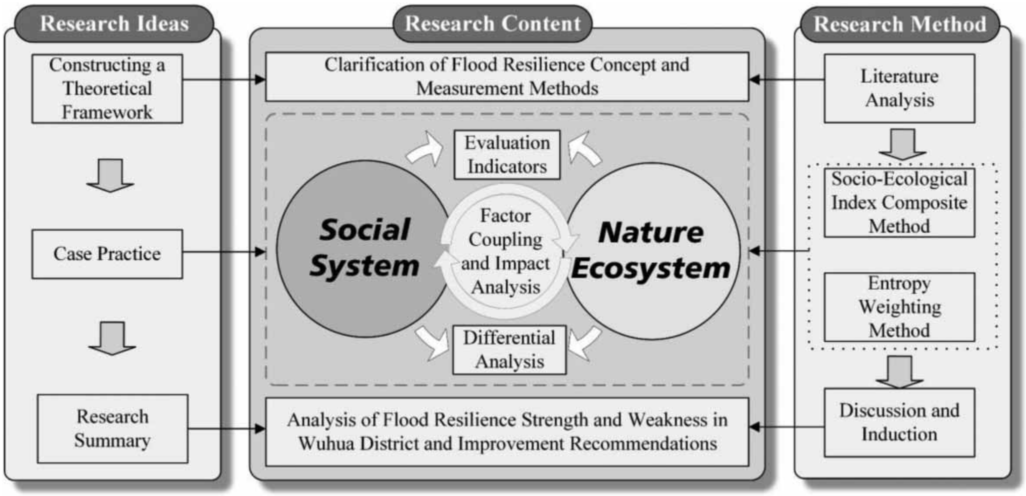


Figure 1 | Technology roadmap.

the Wuhua District, and call for the current urban planning in Wuhua District. From the perspective of resilience, optimization suggestions were put forward to provide decision-making frameworks for urban flood control and disaster risk reduction.

2. STUDY AREA

The core area of the Wuhua District in Kunming is located in the northwestern part of the main urban area of Kunming in Yunnan Province. There are many enterprises, institutions, universities, and scientific research institutions in this area (Figure 2). The region has a subtropical plateau monsoon climate. In summer and autumn, the southwestern warm and humid airflow from the Bay of Bengal, the Indian Ocean, and the southeastern warm and humid airflow from the Beibu Gulf also affect the area. The main flood season is June to August every year. The rainfall is concentrated over these

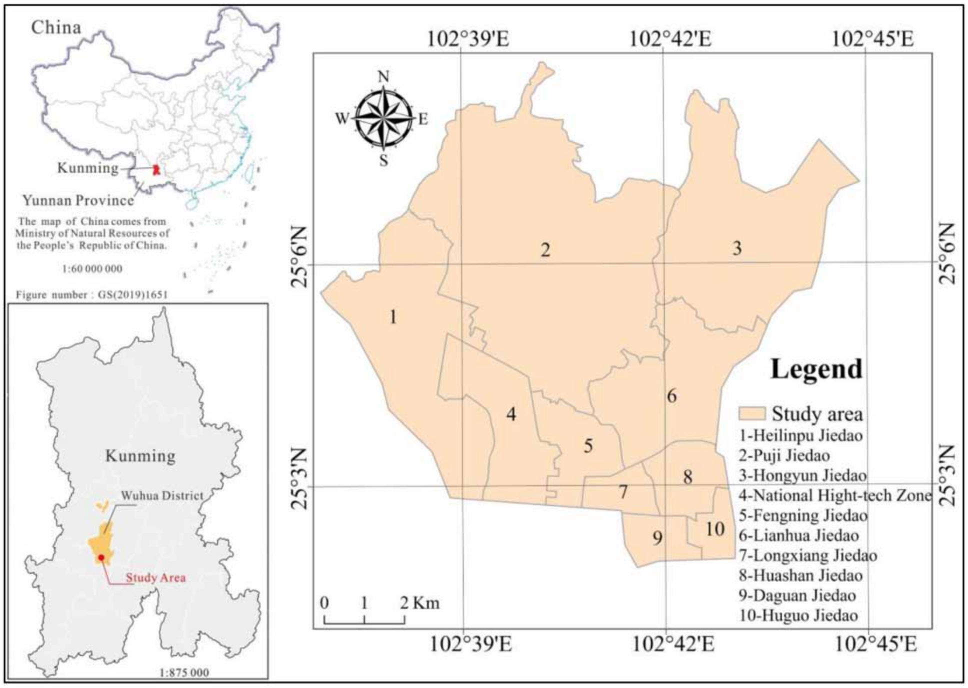


Figure 2 | Study area.

months, and the rainfall duration is short. Flood disasters occur straightforwardly. In recent years, the study area has experienced recurrent occurrences of natural disasters, including rainstorms and floods. The northern part of the study area is mountainous, and mountain torrents referred to as flood disasters affect the study area. In the rainy season, floods carry sediments in urban pipelines, which can easily block the pipeline route and increase the flood control pressure in the city. However, downstream of the main urban area of Kunming is adjacent to Dianchi Lake. Generally, the maximum height difference between the normal pool level of Dianchi Lake and the elevation of the central part of the main urban area of Kunming is only 3 m, which has a strong inhibitory effect on the flood discharge capacity of urban rivers. The water level in the river channel entering Yunnan also drives jacking on tributary ditches and in rainwater pipes in the Drainage River, which seriously affects the drainage capacity of drainage systems in surrounding areas, including the study area. The rainwater in the area cannot be discharged smoothly, resulting in flooding and even jacking back irrigation water and river overflow (Liu 2020). Therefore, the main urban area of Kunming faces great challenges in managing flood disasters.

3. DATA AND METHODS

3.1. Data acquisition

The statistical datasets used in this article cover 10 parts in the core area of Wuhua District, Kunming City. Data mainly include (1) digital elevation model (DEM) data, with a spatial resolution of 12.5 m, derived from the Alaska Satellite Facility (ASF); (2) high-resolution remote sensing data, with a spatial resolution of 10 m and the imaging time on 12 March 2022; (3) land use data, mainly derived from different land use types, including green land, construction land, road network, water system, etc., derived from the People's Government in Wuhua District, Kunming City; (4) gross domestic product (GDP) data and population data of the study area derived from the Kunming Statistical Yearbook 2020; (5) the distribution of pumping stations data and water purification plants data derived from the Kunming Drainage Facilities Management Co., Ltd (Table 1).

In this context, the land use data, as depicted in Figure 3, have been categorized based on the first-level classification of land use types outlined in China's updated 'Current Land Use Classification' national standard. The ultimate land use attribute categories encompass cultivated land, forest, grassland, shrub land, wetland, water bodies, artificial surfaces, and bare land. This article will extract the area of different land use types in its field as the research variable.

The calculation of the normalized difference vegetation index (NDVI) in the study area is executed by utilizing the near-infrared and red bands from high-resolution Sentinel-2 remote sensing images.

The vegetation coverage calculation method employed in this study is NDVI, which stands for the NDVI, also referred to as the standardized vegetation index. NDVI is a widely recognized and classic vegetation index within academic remote sensing methodologies for estimating vegetation coverage (Neinavaz *et al.* 2020). The calculation of NDVI is presented as follows (Equation (1)):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}} \tag{1}$$

Table 1 | Data types and sources in the study area

Name	Data format	Main attributes	Data sources
DEM	GEOTIFF	Altitude	ASF
Land use	Shapefile	Land use type	Kunming Wuhua District People's Government
Pumping station	Shapefile	Name	Kunming drainage company
Water purification plant	Shapefile	Location, design scale, and sewage receiving area	
Sentinel-2	GEOTIFF	Spectrum	Sentry series satellite scientific research data center
Social data	Excel	GDP of each subdistrict, total population of each age stage, population with university degree or above, etc.	Kunming statistical yearbook

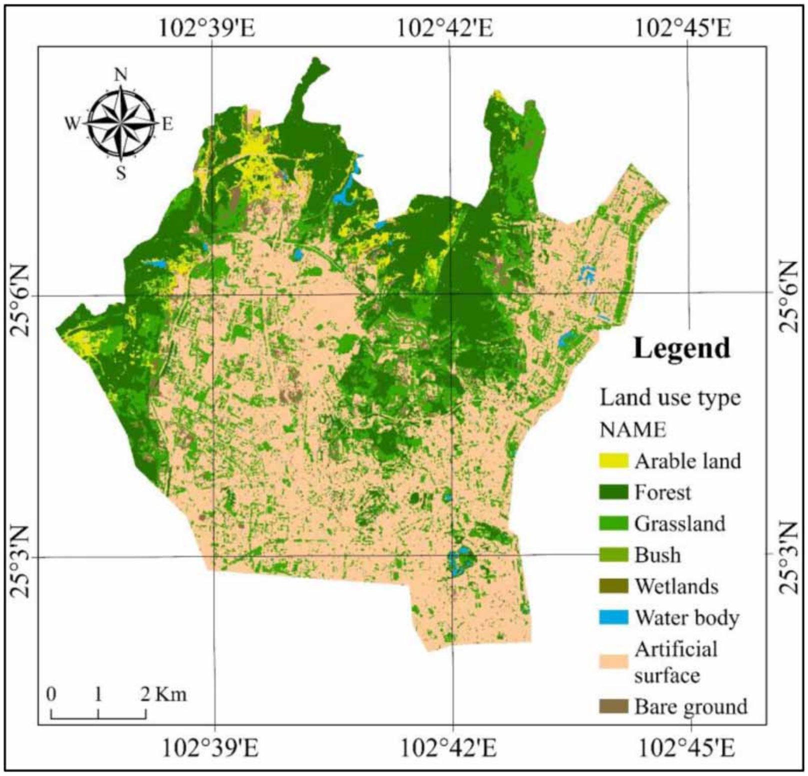


Figure 3 | Land use map.

In this context, NIR represents near-infrared, while R denotes red. The outcomes of the NDVI calculations are illustrated in Figure 4.

Figures 5–7 illustrate the spatial distribution of Chinese restaurants, businesses and service areas, schools and medical centers, village residences, and water conservation facilities along each street within the study area.

3.2. Method

3.2.1. Modeling of social-ecological composite index

The term 'social-ecological system' (also referred to as a 'composite human-earth system' or 'human-nature complex system') denotes the intricate interplay between human society and the environment. It is characterized by complexity, nonlinearity, uncertainty, and multilayered nesting, which collectively define a coupled system (Wang *et al*. 2020; Gain *et al*. 2020). In the past, urban systems primarily encompassed the interconnected relationships among social, ecological, and economic components. However, social-ecological systems, as complex adaptive systems, intimately intertwine human society (social systems) and the natural environment (ecosystems). The social-ecological system constitutes a vast and intricate framework, encompassing human beings, the natural environment, and various social elements such as the economy, politics, history, culture, governance, and consciousness. Within this system, alterations in one element can trigger a cascade of reactions in other elements (Sun & Yao 2019). The concept of the socio-ecological system has successfully analyzed the intricate interactions between humans and the environment on a regional scale. It is grounded in the notion that the division between social and natural systems is arbitrary and artificial (Berkes *et al*. 2000), implying that the connection between social systems and natural ecosystems can be delineated based on the subject matter, characteristics, intentions, and the nature of the study (Liu *et al*. 2023). Socio-ecological systems have been influenced by natural disaster risk strategies that often prioritize disaster response over disaster prevention measures (Vázquez-González *et al.* 2021). Thus, the socio-ecological composite index method (Kotzee & Reyers 2016) adopted in this article was used to measure and analyze the level of flood resilience in the urban system by selecting the social and ecological factors influencing urban flood resilience as evaluation indicators and assigning weights to factors by the determination of scientific and objective weights.

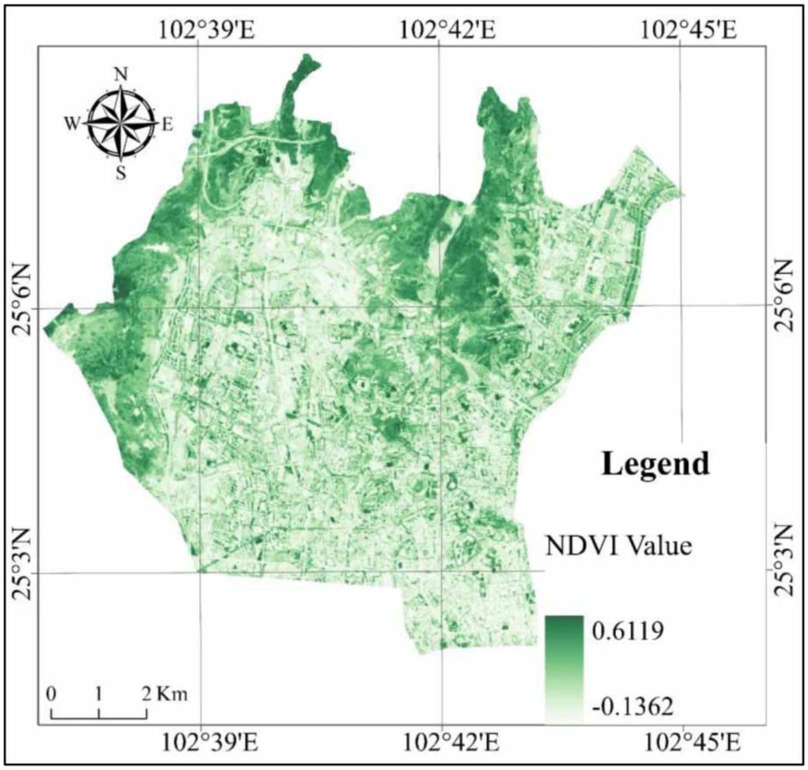


Figure 4 | Vegetation cover map.

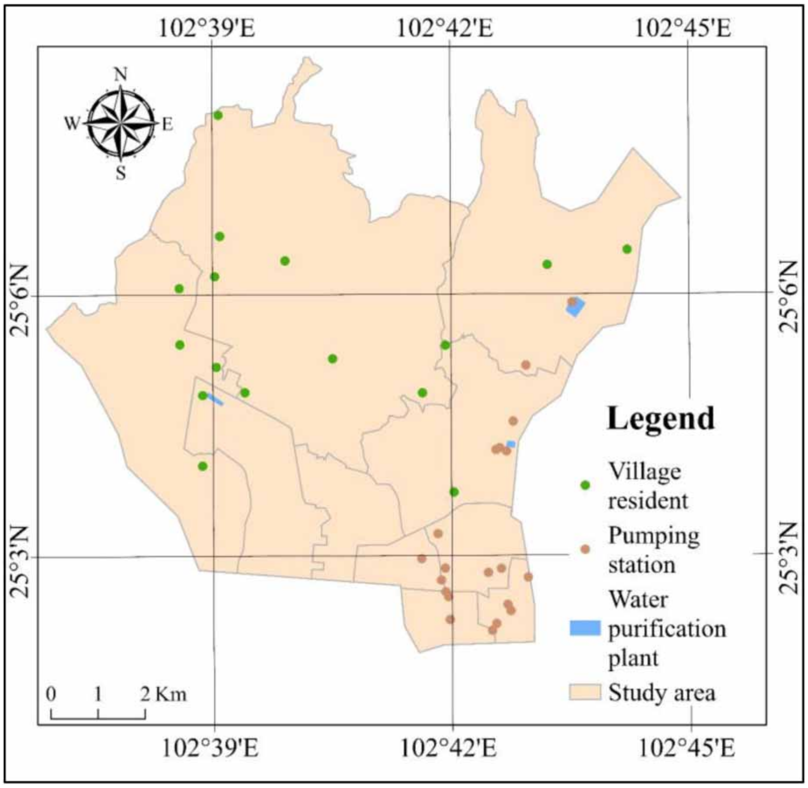


Figure 5 | Distribution diagram of water pump.

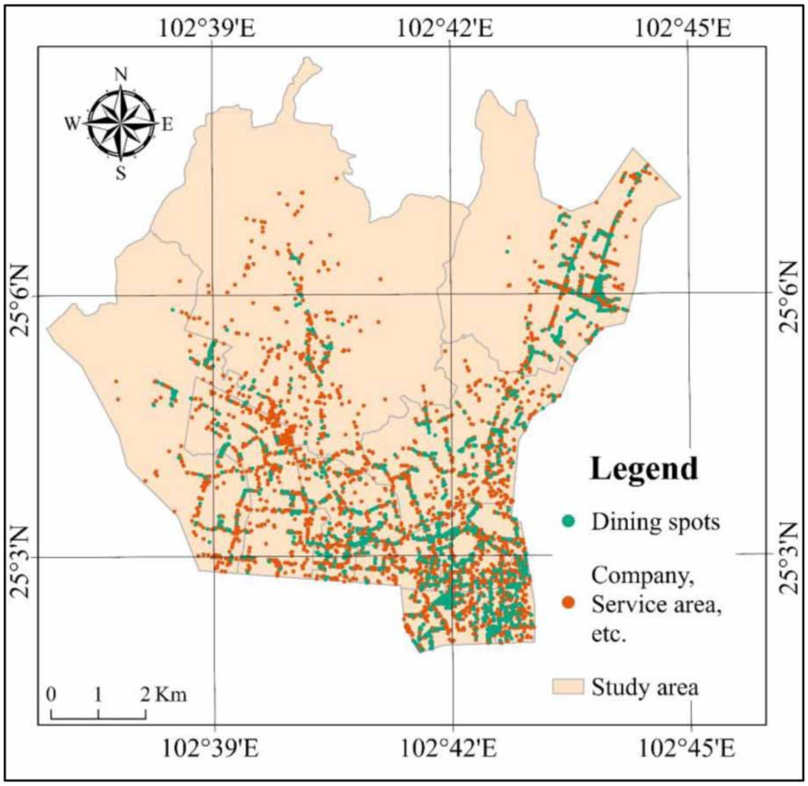


Figure 6 | Company distribution.

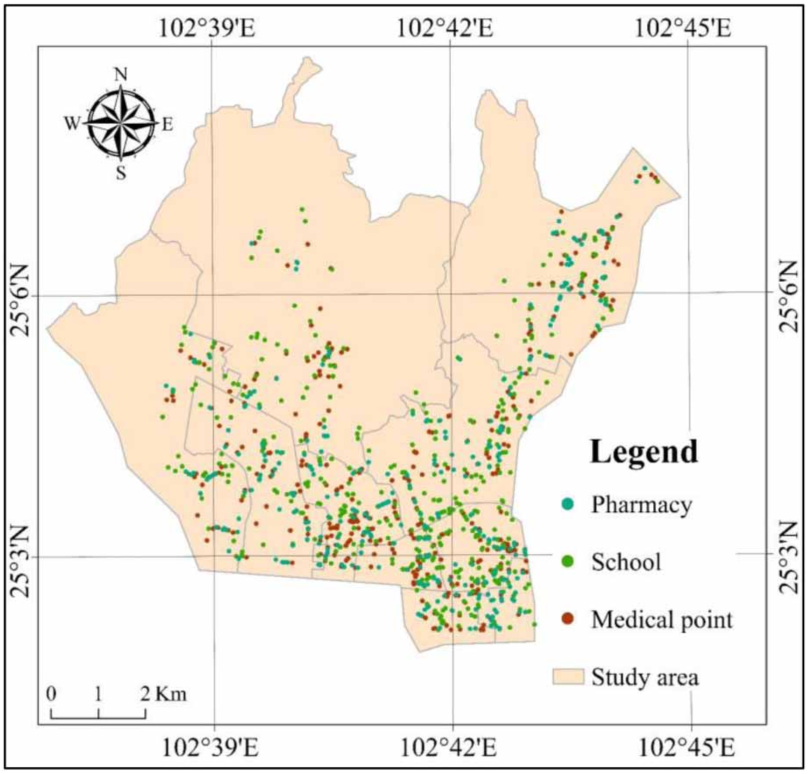


Figure 7 | Distribution map of schools and medical points.

3.2.2. Quantifying urban flood resilience

Urban flood resilience encompasses a multifaceted concept where different indicators play distinct roles in determining resilience. To accurately and scientifically represent the interplay between the indicators in the system, varying weights are assigned to the evaluation indicators, reflecting their relative importance. This approach ensures a more objective and comprehensive assessment of urban flood resilience. The entropy weight method is a scientific and objective weighting method. It determines the weight of indicators in the comprehensive evaluation system according to the information relating to the degree of variability of each indicator in each matrix in the process of indicator evaluation. The smaller the entropy value of the indicator, the larger the piece of information and the greater the weight of the indicator. On the contrary, the larger the entropy value, the smaller the piece of information and the lighter the weight of the corresponding indicator. The entropy weight method provides the objective and simple calculation of the weight of indicators. Compared with subjective methods such as the AHP, it has an absolute accuracy. Moreover, the weight determined in this method can be modified, which indicates its high level of adaptability.

The calculation of weight in the entropy weight method was done as follows:

Step 1: See Equations (2) and (3) for index standardization, where I represents Street ($I = 1,2,3, \ldots, n$) and j represents index ($j = 1,2,3, \ldots, m$).

$$\text{Positive indicators: } x'_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij)} - \min(x_{ij})} \tag{2}$$

$$\text{Negative indicators: } x'_{ij} = \frac{\max\,(x_{ij}) - x_{ij}}{\max(x_{ij)} - \min(x_{ij})} \tag{3}$$

where x'_{ij} is the standardised value; x_{ij} is the original value of the jth index of the ith street.

Step 2: Normalize the index and calculate the proportion of the jth index in the ith street (Equation (4)).

$$X_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{4}$$

Step 3: Calculate the information entropy of the index (Equation (5)).

$$e_j{:}e_j = -\frac{1}{\ln n}\sum_{i=1}^{n}(X_{ij} \times \ln X'_{ij}),\ (0 \le e_j \le 1) \tag{5}$$

where n is the total number of samples (blocks).

Step 4: Calculate the difference coefficient and indicator weight of each indicator (Equations (6) and (7))

$$g_i = 1 - e_j,\ j = 1, 2,\ \cdots, m \tag{6}$$

$$w_j = \frac{g_j}{\sum_{j=1}^{m} g_j},\ j = 1, 2,\ \cdots, m \tag{7}$$

Following the determination of weights for each indicator, it is essential to compute the ultimate urban flood resilience scores for each street. Equation (8) outlines the precise calculation procedure:

$$C_i = \sum_{j=1}^{m} x'_{ij} w_j, j = 1, 2, \cdots, m \tag{8}$$

where C_i is the resilience score of the ith street.

4. RESULTS AND ANALYSIS

4.1. Index system

Based on the research index system developed by Kotzee & Reyers (2016), Satour *et al.* (2020), Chen *et al.* (2018), and other scholars, and considering the availability of data, this study selected 18 indicators relating to social, ecological, and economic dimensions to measure the urban flood resilience. (1) The resilience of urban floods and waterlogging is manifested in the adaptation to these disasters. Among them, the resilience and adaptation of cities were closely related to the social and economic resilience of cities (Wang *et al.* 2021). In this article, GDP, average housing area per capita, and the number of companies, service areas, and hotels were selected from the economic perspective. (2) The social resilience in the process of urban development is manifested in the capacity of social security and urban growth potential following the short-term pressures and cumulative impacts after the exposure of the city to disasters (Wang *et al.* 2020). Therefore, this article selected nine indicators covering four aspects such as population structure, medical care, education, and transportation. (3) Urban ecological resilience plays an important role in resisting flood disasters, recovering from trauma, and adapting to the new environment. Urban flood risk is mainly manifested as the sharp reduction in the public green space in an urban construction land and the defects in infrastructure such as the sewage system and the water purification system (Wang *et al.* 2019). Thus, this study used vegetation coverage and flood control facilities to evaluate urban flood resilience. In the previous studies, the more balanced the structure of urban subsystems, the smaller the difference between cities and the lighter the index weight (Batica 2015) (Table 2).

4.2. Index weight

First, this article determined urban flood resilience and then established the evaluation index system and the level matrix using the ecological composite index method. Second, since each set of index data of each street has different units and attributes, this article standardized the index data of each street by calculating the index weight using the entropy weight method to reduce the impact of different dimensions and the magnitude of data. In the process of standardization, we classified the indicators into positive and negative returns. Among them, the indicator producing positive returns on urban flood resilience was marked as P (positive), and the indicator producing negative returns on urban flood resilience was marked as N (negative).

In this article, P indicators included GDP, population with a bachelor's degree or higher, water conservancy facilities, hospitals and clinics, schools, government agencies and offices, companies and service areas, bus stations, highways, hotels, river channel length, pipeline length, ditch length, and vegetation coverage. N indicators included housing area per capita, dependency ratio, children under 5 years old and people over 65 years old.

Since there are zero values in the process of standardization, to ensure the reliability of the experiment, we shift all the values in the standardized horizontal matrix. The translation amount is 0.001.

Following the acquisition of the standardization level matrix, the subsequent step involves utilizing Tables 3–5 to compute the entropy, difference coefficient, and information utility value for each indicator. These values are then normalized to derive the entropy weight for each indicator. The larger the information utility value, the more information it corresponds to. Finally, the weight of each index under the model is obtained.

According to the weights of the indicators in Table 2, we analyze that the river length has the greatest impact on the urban flood resilience, followed by the expressway, the population with a bachelor degree or above. These three indicators respectively represent a city's flood discharge capacity, transportation road resources, and social innovation capability.

Table 2 | Evaluation index system of urban flood resilience in Wuhua District

Target layer	Criterion layer (weight ratio)	Indicator layer (weight ratio)	Meaning and nature of indicators
Urban flood resilience	Economic resilience (13.8%)	Annual GDP of each street (3.9%)	Reflect the overall economic vitality of each subdistrict
		Per capita housing area (1.9%)	Reflecting the people's economic and living standards
		Company and service area (4.3%)	Reflect the direction of social and economic development
		Hotels (3.7%)	Reflect social and economic vitality
	Social resilience (49.1%)	Hospital clinics (5.2%)	Reflect the social medical security ability
		Children under 5 years old (2%)	Reflect the number of social vulnerable groups
		Elderly over 65 years old (3.4%)	Reflect the number of social vulnerable groups
		Dependency ratio (2.8%)	Also known as the coefficient of dependency, it is the ratio of the number of persons of nonworking age to the number of persons of working age in the population. Reflect the number of people who bear the support per capita
		Bus station (3.4%)	Reflect the perfection of urban hardware facilities
		Highway (12.8%)	Reflect the rationalization of traffic road resource allocation
		Schools (4.8%)	It reflects the perfection of the structure of the education system
		Population with bachelor degree or above (7.6%)	Reflect social innovation ability
		Government agencies and offices (7.1%)	Reflect the public management ability of the government
	Ecological resilience (37.1%)	River course (15.3%)	Reflect urban flood discharge capacity
		Pipeline (5.3%)	Reflect the construction degree of urban flood control facilities
		Ditches (6.2%)	Reflect urban flood discharge capacity
		Pump station and purification plant (7.3%)	Reflect urban ecological resistance and internal circulation capacity
		Vegetation coverage (3%)	Reflect the city's ability to prevent and avoid disasters

4.3. Urban flood resilience score

We substituted the weight of each index in the proposed urban flood resilience calculation formulas with the original data matrix of each street to obtain the flood resilience score for each street and map the flood resilience scores; the GIS-based thematic map of the horizontal distribution of flood resilience in the Wuhua District was drawn.

Table 3 | Standardized level matrix a

Name	GDP (100 million yuan)	Population with bachelor degree or above	Housing area per capita (square meters/person)	Dependency ratio
Huguo Street	0.001	0.131	0.938	0.421
Daguan Street	0.345	0.249	0.968	0.211
Longxiang Street	0.176	0.202	0.975	0.449
Huashan Street	0.607	0.641	1.001	0.735
Fengning Street	0.516	0.248	0.982	0.718
Lianhua Street	1.001	1.001	0.873	0.878
National High-tech Zone	0.306	0.662	0.864	0.956
Hongyun Street	0.554	0.513	0.672	1.001
Heilinpu Street	0.291	0.110	0.956	0.815
Puji Street	0.174	0.086	0.989	0.698

Table 4 | Standardized level matrix b

Name	Child	Elder	Water conservancy facilities	Hospital clinic	School	Government agencies and offices
Huguo Street	0.704	0.225	1.001	0.434	0.081	0.136
Daguan Street	0.779	0.001	0.667	0.576	0.173	0.017
Longxiang Street	0.840	0.242	0.333	0.632	0.368	0.068
Huashan Street	1.001	0.367	0.667	0.727	0.713	0.314
Fengning Street	0.608	0.557	0.001	1.001	0.517	0.178
Lianhua Street	0.734	0.772	0.833	0.887	1.001	0.068
National High-Tech Zone	0.618	0.948	0.167	0.708	0.184	0.051
Hongyun Street	0.558	1.001	0.500	0.915	0.333	0.009
Heilinpu Street	0.476	0.842	0.001	0.406	0.356	0.085
Puji Street	0.001	0.897	0.001	0.462	0.563	0.001

Table 5 | Standardized level matrix c

Name	Company, service area	Bus stop	Highway	Hotel	Vegetation coverage	Channel length	Line length	Trench length
Huguo Street	0.543	0.001	0.001	0.724	0.923	0.890	0.158	0.001
Daguan Street	0.560	0.270	0.001	0.621	0.928	0.001	0.299	0.115
Longxiang Street	0.406	0.191	0.001	1.001	1.001	0.001	0.424	0.459
Huashan Street	1.001	0.540	0.001	0.828	0.775	0.001	0.853	0.807
Fengning Street	0.642	0.381	0.001	0.966	0.944	1.001	0.138	0.190
Lianhua Street	0.973	1.001	1.001	0.759	0.854	0.425	0.143	0.107
National High-Tech Zone	0.752	0.706	0.353	0.345	0.601	0.001	1.001	0.693
Hongyun Street	0.940	0.603	0.235	0.069	0.609	0.446	0.382	0.950
Heilinpu Street	0.352	0.286	1.001	0.724	0.942	0.001	0.001	0.096
Puji Street	0.596	0.492	0.588	0.035	0.466	0.001	0.864	1.001

Based on the socio-ecological composite index model, this article modeled and analyzed urban flood resilience by comprehensively considering the social, ecological, and economic factors.

The results are as follows: (1) based on the comprehensive evaluation results, the average flood vulnerability index of the 10 studied regions in the Wuhua District was 0.39, indicating that these regions are medium vulnerable zones. However, there were obvious differences in the level of flood and waterlogging resilience among various streets and regions, which were not entirely caused by one factor. Among them, the Lianhua subdistrict had a wider distribution of vulnerability to flooding (0.72). The Longxiang subdistrict was the least vulnerable zone (0.22). This reflects the uneven distribution of flood and waterlogging resilience in various regions of the Wuhua District and large individual differences between regions. (2) The vulnerability of streets in the Wuhua District was assessed (Figure 8) using the distribution map of urban flood and waterlogging vulnerability showing the vulnerability scores in the Wuhua district, which were divided into grades. Kunming National High Tech Industrial Development Zone, Lianhua subdistrict, is the central area of Wuhua District, and the flood resilience gradually decreased from the inside toward the outside of this study area. (3) Based on the overall spatial characteristics, the flood resilience of streets in the Wuhua District showed a certain degree of spatial aggregation. Lianhua, Hongyun, Huashan, and Heilinpu subdistricts with strong flood resilience are spatially adjacent to Kunming National High-Tech Industrial Development Zone. Similarly, the streets with low flood resilience, such as Puji, Fengning, Longxiang, Daguan, and Hugo, are spatially adjacent and have a certain degree of aggregation. (4) In terms of population, the number of vulnerable people, such as children and the elderly, did not have a large negative impact on urban flood resilience. The dependency ratio, i.e., the number of vulnerable groups that need to be taken care of by adults, had a more direct impact on the resilience of urban floods. The higher the dependency ratio, the greater the responsibility and pressure on adults in this city. As a

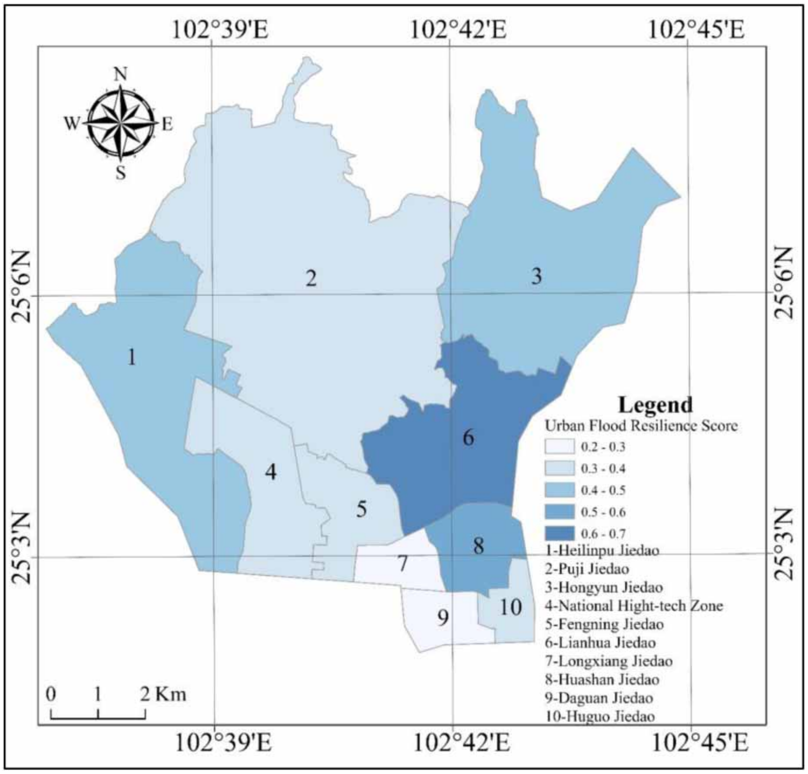


Figure 8 | Distribution map of urban flood resilience scores in Wuhua District.

result, the difficulties faced by these adults are more severe in the face of sudden floods. Based on the distribution map showing the dependency ratio of each street, the street with the highest dependency ratio ranked the lowest in the overall flood resilience in the Wuhua District. Among them, the Daguan subdistrict with the highest dependency ratio had a low ranking of flood resilience. (5) In terms of economy, the relationship between simple GDP and urban flood resilience was not obvious because the rationality of the urban economic and industrial structures was not represented. At the time of the flood disaster, only a city with superior economic and industrial status could better resist the impacts of flood disaster, recover its vitality faster, and adapt to environmental changes with the provided strong economic support. Similarly, based on the Point of Interest (POI) distribution map and land use planning map of the Wuhua District, we can draw a conclusion that the streets with strong flood resilience have more suitable economic construction facilities than others.

5. DISCUSSION

The rapid evolution of global climate change and urbanization has ushered in a multitude of factors that contribute to urban flooding disasters. The traditional approach of relying on extensive municipal drainage system facilities to combat urban flooding is now considered outdated and, in fact, may further strain the city's financial resources (Ullah & Zhang 2020; Ziegelaar & Kuleshov 2022; Zhao *et al.* 2023). In contrast to a substantial body of previous research focused on enhancing urban drainage systems, the prevailing direction in contemporary urban flooding research is the augmentation of flood resilience. Concurrently, scholars have recognized that modern urban flood disasters are not solely an infrastructure concern; they also entail social dimensions (Jiang *et al.* 2023). Consequently, flood disaster prevention and management should incorporate a comprehensive assessment of various factors within urban areas before implementation. Taking the Wuhua District of Kunming City, China, as the study area, this article used the socio-ecological composite index model to evaluate the urban flood resilience in various regions of the Wuhua District and determined the impact of various types of factors on the resistance and adaptation of the city to and its recovery from flood disasters; thus, drawing the map showing the distribution of flood resilience levels in the study area. In contrast to the conventional 'one-time complete solution' approach to flood prevention and control, this article takes into account the actual conditions of disaster resilience within urban flood scenarios, especially in the context of global climate change. It adopts a perspective of 'coexisting with floods' by integrating social and ecological considerations. This approach allows for the identification of potential issues, such as weak flood resilience in specific areas related to facilities or environmental aspects. As a result, the study offers innovative ideas and methods for flood prevention and control in the study area. The findings of this research can serve as a foundation for decision-making in subsequent urban planning and development. Moreover, this approach is transferable and can be applied to other rapidly urbanizing cities, providing valuable insights for areas experiencing similar challenges.

5.1. Main factors influencing urban flood resilience

As depicted in Figure 8, there is a spatial connection between the urban flood resilience of every street within the 10 subdistricts in the study area. The influencing factors of the spatial distribution of urban flood resilience, quantified using GIS and modeled through the socio-ecological composite index model, revealed several variables significantly associated with urban flood resilience. These variables fall into various categories, such as river length, high-grade highway, population with higher education levels, pump station, purification plant, and more. These are primarily summarized as follows:

(1) Traffic-related factors: The more developed the traffic infrastructure of a city, the stronger the emergency resistance, recovery, and adaptation of the city in the face of flood disaster. In today's era, the performance of various functions of the city needs to be improved by transportation. The improvement of transportation facilities is closely related to the internal circulation in the urban system. Before the occurrence of flood disasters, the implementation of the government's emergency defense policy needs the support of the traffic road network, and for commuting, people also need to use transportation systems that are supported by the urban traffic infrastructure. After the flood disaster, disaster relief and material transportation also need the support of the urban traffic road network. The implementation of the urban system cannot be achieved independently of the traffic road network. At the same time, according to the previous research results, the road traffic infrastructure is the lifeline of a city. The more developed the traffic infrastructure, the higher the efficiency of internal circulation in the urban system and the greater the city's ability to resist disasters. This is consistent with the results of this study.

(2) Waterlogging prevention infrastructure: The degree of the efficiency of a city's waterlogging prevention infrastructure directly affects its ability to store, discharge, and purify water resources (Chen *et al.* 2023). In the face of flood and waterlogging disasters, the utilization efficiency of water resources is directly related to the city's ability to resist disasters and its resilience after disasters (Li *et al.* 2022). In the event of a disaster, poor drainage facilities may directly cause 80% resistance loss in the city. After the flood disaster, the city's safe, drinkable, and pure water resources directly affect its recovery ability. In the aftermath of a disaster, the general public is often the most severely impacted, with their daily survival hinging on access to drinking water and specific potable water resources essential for postdisaster reconstruction initiatives. Therefore, in this study, the high correlation between water conservancy facilities and urban flood resilience conforms to the actual situation and has significant relevance.

(3) Population quality: The highly educated population in a city represents the innovation capacity of the city. Individuals with higher levels of education tend to exhibit greater resilience when confronted with disasters. Innovation can promote the optimization of industrial structures to increase economic vitality and finally lead to the enhancement of urban flood resilience. The occupancy of highly educated talents and innovative enterprises will improve the overall economic vitality of the city and thus enhance its flood resilience. The augmented knowledge and competencies of highly educated individuals have heightened their awareness of disaster preparedness, consequently fortifying their resilience in the face of disasters. However, there is a lack of relevant research on this topic.

(4) Government: The Chinese government has gained a wealth of valuable experience in the prolonged struggle against flooding disasters. In response to various natural disasters and various types of emergencies caused by them, emergency laws and systems for the management of these disasters, such as disaster prevention, mitigation, disaster relief, and postdisaster reconstruction, are adopted by the government, which protect people's lives and provide property safety and social and economic stability in response to natural disasters. They have also played a key role in maintaining social order. When a disaster occurs, the government's crisis management competencies will initially play a role. The government will use its unique capabilities, authority, and coercive force to provide disaster relief at the fastest speed and in the shortest time frame so that the interests of the broad mass of people can be effectively protected (Peng *et al.* 2023). In a subadministrative region, a larger number of agencies and departments come under the jurisdiction of the government, and the government's emergency policies can be followed by people sooner and faster; moreover, the government's emergency

measures can be implemented sooner and also more efficiently, and thus, the safety of people can be guaranteed more effectively. Similarly, after the disaster, the government can also use its geographical advantages to find the most severely affected areas through the departments under its jurisdiction in different regions and then work out relevant solutions, in turn, to ensure the protection of public interests to the greatest extent and manage the social operating system and economic recovery at maximum efficiency.

5.2. Assessment of flood resilience in Wuhua District from socioecological perspectives

The results of this article showed that the 10 regions in Wuhua District overall represent the areas with medium-level urban flood resilience, but the difference in the degree of flood resilience between individual regions, with streets as a unit, was obvious, and the degree of spatial differentiation was not completely linked to the economic development level of Wuhua District. Therefore, through an in-depth analysis of the components of urban flood resilience and evaluation of urban flood resilience from the socio-ecological perspective, we can draw the following conclusions:

(1) From the perspective of urban infrastructure, the more stable the industrial structure, the stronger the resilience of urban floods. The urban planning should aim to adjust the industrial structure, pay attention to the comprehensive development of all streets in the Wuhua District, promote the economic diversification of economic industries, reduce the intensity of tax competition in high-tech industries, and strengthen economic cooperation and exchange in all streets to improve the resistance and recovery ability of the city in the face of flood disaster.

(2) From the sociocultural perspective, the per capita dependency ratio and the number of highly educated people in the urban system had significant impacts on urban flood resilience. In the face of flood disasters, the higher the per capita dependency ratio, the more the manpower for urban flood prevention emergency and the more early warning, crowd evacuation, and urban recovery and construction, and thus, the stronger the urban flood resilience. Therefore, the city should reasonably distribute the urban population, fulfill the positive role of the market in resource allocation, and improve the social security system for vulnerable groups. At the same time, it should establish an incentive mechanism for scientific research to encourage high-tech research and development, develop creativity in the social system and rationality in the industrial structure, refine the talent return policy, and improve the talent compensation system and the overall urban flood resilience of the Wuhua District with the concept of mutual benefit, help, and unity to strengthen the resilience and adaptation of the urban system in the fight against flood disasters.

(3) From the perspective of ecological infrastructure construction, the urban system should strengthen the flood prevention infrastructures, such as pumping stations, water supply, drainage pipelines, and storage reservoirs, that should be upgraded and maintained regularly. Priority should be placed on the improvement of hillside vegetation development within urban areas, with a focus on preserving the diversity, intricacy, and stability of the ecological environment. By implementing these strategies, urban flood resilience can be significantly bolstered.

6. CONCLUSION

This article has formulated an assessment framework for urban flood resilience indicators using a socio-ecological composite index approach. It quantifies the spatial disparities in urban flood resilience and offers valuable insights and methodologies for urban flood prevention within the context of global climate change and urbanization. This research delves into the underlying factors influencing urban flood prevention and control at a deeper level, making it a foundational resource for urban planning decision-making. It presents a novel approach and model for the prevention and control of urban floods in a normalized context.

This study found that the level of flood resilience of the Wuhua District in Kunming was higher in the urban area than in the suburbs, and the flood resilience of each street in the urban area showed undulation, i.e., the flood resilience of two sides of the area was greater than that of the central area. In previous research on urban flood resilience, the resilience level of regions was mostly concentrated in the city center and gradually decreased outward from the center. The streets of the Wuhua District are located in the central area of Kunming. Meanwhile, this article studied the overall urban flood resilience of the Wuhua District by taking the streets as an analysis unit, and the research perspectives were more microscopic than in other studies. Therefore, the micro-scale horizontal distribution of urban flood resilience was more discrete, and the regional differences were more prominent than those of the macro-scale distribution.

Through our results, the distribution of traffic facilities in this study also played an important role in enhancing urban flood resilience. Traffic infrastructure is an important medium of material transmission in the urban system. It directly affects the corresponding capacity, capacity recovery, and transfer capacity within the city, affecting the level of flood resilience in different areas of the city. The distribution of urban underground pipe networks, such as urban drainage pipes, was closely related to the urban traffic network. In areas with developed road networks, the more comprehensive the distribution of drainage pipes, the stronger the regional flood resilience.

The construction of flood and waterlogging resilient cities requires shifting the focus for their development from the increase in quantity to the improvement of quality by realizing the organic integration of urban systems, enhancing the resilience and adaptation of cities to flood and waterlogging disasters, and reducing the vulnerability of cities to meet the needs of China's new and resilient urbanization. At the same time, different regions have different ecological environments, geographical conditions, and cultural backgrounds. Therefore, when strengthening flood resilient construction, each city should consider and combine its characteristics and conditions and cannot adopt other urban construction plans for improving flood resilience.

In future research, there is a need to refine the urban flood resilience evaluation model, broaden the scope of the evaluation system to encompass more representative indicators, and delve deeper into the coupling relationships that arise within the urban system. These efforts are essential for enhancing the model's effectiveness in elevating urban flood resilience. In addition, expanding the examination of how urban flood resilience evolves in a constantly changing environment is crucial to accurately measure and quantitatively express urban flood resilience.

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CONSENT TO PARTICIPATE

All the co-authors agreed to participate in the research.

CONSENT TO PUBLISH

All the co-authors agreed to publish the manuscript.

AUTHORS CONTRIBUTIONS

D.H. and Z.X. wrote the paper and processed the data, F.J. and J.X. provide guidance for this paper, X.F. and R.L. revised the language, D.Z. corrected the chart, and L.Z., X.Y., Y.B., Q.W., H.Z., B.W., and Q.W. provided part of data. All authors discussed the results and contributed to the final manuscript.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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