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# Resilience-Vulnerability Balance and Obstacle Factor Analysis in Urban Flooding: A Case Study in the Qinghai–Tibetan Plateau

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**Abstract:** Under the combined influence of climate change and urban development, the risk of urban flooding caused by extreme weather events has increased significantly, making assessing flood vulnerability and resilience increasingly crucial for urban flood management. With the 45 counties in Qinghai Province as the research objects, the hazard risk of flood and exposure are combined to study their vulnerability. At the same time, resilience is evaluated by the indicators selected from four dimensions (society, economy, environment, and infrastructure). Through Z-scoring, the vulnerability and resilience of each county are clustered into four groups to explore their associations from a spatial balance perspective. Obstacle factor analysis is introduced to summarize the key factors affecting the improvement of urban resilience in Qinghai Provence. The results show that the eastern areas of Qinghai experience high vulnerability to flooding because of high levels of hazard and exposure. What is more, Xining, Haidong, and Haixi experience a high level of resilience. A strong spatial mismatch between vulnerability and resilience exists in Qinghai, with 24 counties (58%) being self-adapted, 8 counties (18%) over-abundant, and 11 counties deficient in terms of nature–nurture. The length of levee and number of beds in medical institutions are the main obstacles to resilience in Qinghai. The research results can provide a theoretical and scientific basis for future urban flood management and resilience development in the Qinghai–Tibetan Plateau.

**Keywords:** Qinghai Province; flood disaster; resilience assessment; Z-score; obstacle factor analysis; resilience enhancement strategy

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## 1. Introduction

The number of casualties and economic losses from natural catastrophes has increased along with urbanization, urban population growth, and economic agglomeration [1]. Globally, the frequency of natural catastrophes has increased significantly over the past three decades, with floods being the most frequent type of disaster [2]. The increased risk of climate change, coupled with ecological degradation and low coping capacities, has resulted in an increased risk of flooding globally and an increase in the number of regions affected by floods [3,4]. According to statistical information from China's flood and drought disaster bulletin, more than 100 cities in China are affected by flooding every year [5]. Furthermore, over a period of 40 years (1980–2020), China experienced economic losses equivalent to around 2% of its GDP, affecting approximately 200 million people in addition to deaths, injuries, and homelessness [6]. In addition, changes in the global climate and urban water cycle processes, leading to natural disasters such as rainstorms, flash floods, and tsunamis, have also increased the frequency of extreme rainstorms and flooding in cities and more severe disaster losses [7–9]. Therefore, improving urban flood resilience and reducing the impact of flooding has become an urgent challenge.

Resilience has become a crucial research focus to address the various threats and risks cities encounter [10]. Organizations and research institutions such as the United Nations International Strategy for Disaster Reduction (UN/ISDR), the Rockefeller Foundation, and the Intergovernmental Panel on Climate Change (IPCC) advocated for the construction of resilient cities [11]. Urban resilience refers to the ability of city systems, including their subsystems, to maintain, recover, and adapt when disturbed [12,13]. Researchers have extended the concept of flooding resilience, which refers to the ability of cities to self-organize after withstanding floods to minimize potential casualties while maintaining socio-economic characteristics [14]. Assessing and predicting urban flood resilience can facilitate proactive planning and resilient infrastructure development, enabling cities to effectively cope with and adapt to natural disasters, thereby mitigating socio-economic impacts [15]. Various institutional activities can be linked by resilience, and resilience can be promoted to help people deal with and adapt to disasters, which reduces the impact of vulnerability to them. In recent years, scholars have comprehensively assessed urban resilience from multiple perspectives. Cutter proposed a community baseline resilience evaluation index system to quantify resilience based on six dimensions: social, economic, infrastructure, institutional, community, and ecological, which is the first attempt to transition resilience from a theoretical framework to operationalized practice [16]. Several scholars have established flood resilience models based on exposure, vulnerability, and adaptability dimensions from resilience characteristics [17,18]. The main assessment methods for urban flood resilience include entropy weighting, hierarchical analysis, principal component analysis, TOPSIS, structural equation modelling, and system dynamics [19–21]. To analyze the main factors affecting urban resilience, the geographically weighted regression and obstacle model was used to quantified the degree of influence of urban resilience factors [10,22]. Several studies have explored urban flooding and climate change in high-altitude regions like the Tibetan Plateau, and revealed character of flood susceptibility, exposure, resilience and vulnerability [23–28].

Despite significant progress in understanding urban flood resilience and evolution, existing research reveals notable deficiencies in exploring the spatial balance between resilience and vulnerability. The spatial relationship of resilience–vulnerability to urban flooding emerges as a pivotal area of inquiry, aiming to dissect and understand the intricate dynamics between urban resilience—the capacity of cities to absorb, recover from, and adapt to adverse events—and vulnerability, the susceptibility of urban systems to damage and dysfunction as a result of such events. Qinghai Province is located in western China and is the main part of the Qinghai–Tibet Plateau. In the context of ongoing global climate change, Qinghai Province has experienced a significant upward trend in annual precipitation, with an increase of 15.8 mm per decade since 1961 [29]. This rate of increase substantially exceeds the national average of 5.8 mm per decade in China, and the 1.4 mm per decade observed in similar latitude regions. Qinghai's unique geography and ecosystems make it especially vulnerable to climate change, resulting in more pronounced impacts on its grasslands, glaciers, snowpack, lakes, and permafrost. This sensitivity leads to greater variability and uncertainty in predicting future climate impacts [30]. What is more, urban areas account for only 0.22% of the province's total land area and are mainly concentrated in river valleys and basins, where multi-level problems such as gully erosion hazards and geological hazards prevail [31]. Precipitation and intensity in Qinghai are unevenly distributed, gradually decreasing from east to west and from south to north [32], exacerbating the region's vulnerability to droughts and floods due to anomalous climatic conditions, resulting in concentrated disaster events. In addition, Qinghai's overall river flood control standards are inadequate, with an imperfect flood control system and various other safety hazards limiting the effectiveness of disaster reduction measures. Disparities in economic development across the province, coupled with different cultural and educational levels, conservative attitudes towards labour skills and ideological beliefs, further exacerbate the province's vulnerability to floods and significantly hamper resilience-building efforts [33,34]. Given the significant disparities in urban natural environments and unbalanced infrastructure conditions in Qinghai, mapping flood vulnerability and resilience is imperative in addressing flood issues. The increased vulnerability underscores the urgent need for detailed studies of flood vulnerability and resilience characteristics, and tailored strategies to mitigate and adapt to these environmental changes in Qinghai. The increased vulnerability underscores the critical need for detailed studies and tailored strategies to mitigate and adapt to these environmental changes in Qinghai.

This study resolved the shortage in the literature on flood vulnerability and resilience in Qinghai by proposing a framework to quantify the spatial patterns of susceptibility and resilience to urban flooding as well as investigate the spatial relationship between vulnerability and resilience. The barrier degree model was used to analyze the barrier factors influencing flood resilience. This research contributes to understanding the levels of vulnerability and resilience in Qinghai and offers targeted improvement suggestions. The results may be further applied to counties in the Qinghai–Tibet Plateau area, giving stakeholders a solid scientific foundation on which to build practical and targeted urban flood mitigation and prevention strategies. This study uses related theoretical, conceptual, and technological advances to apply the geographical balance between vulnerability and resilience to urban flooding research and practical applications. It also makes use of policy implementation, such as urban planning, to enhance urban flood resilience in the future.

## 2. Materials and Methods

### *2.1. Study Site*

Qinghai Province is located in the western region of China (31°36′–39°12′ N, 89°24′–103°04′ E), on the northeastern part of the Tibetan Plateau, with an area of 722,000 km$^2$ and a population of 5.8 million. Regarding its administrative divisions, it governs two prefecture-level cities, Xining and Haidong, and six national autonomous prefectures: Yushu, Golog, Huangnan, Hainan, Haixi, and Haibei, and is composed of 45 counties (Figure 1). Qinghai Province plays a crucial role in conserving water resources, serving as the source of the Yellow River, Yangtze River, and Lancang River. It has 21 counties designated national key ecological function areas, making it an essential ecological function zone and ecological security barrier in China [35]. The precipitation in Qinghai gradually decreases from southeast to northwest, ranging from 15 to 750 mm. The annual precipitation is below 400 mm, with 70% of precipitation occurring between July and September. Most of Qinghai is plateaus and mountainous, and the main topographic units are the Qilian Mountains, Kunlun Mountains, Tanggula Mountains, Bayankala Mountains, Qaidam Basin, Qingnan Plateau, and Loess Plateau. Influenced by topography, extreme storms, and urban development, urban flooding disasters in Qinghai Province are increasingly intensifying.

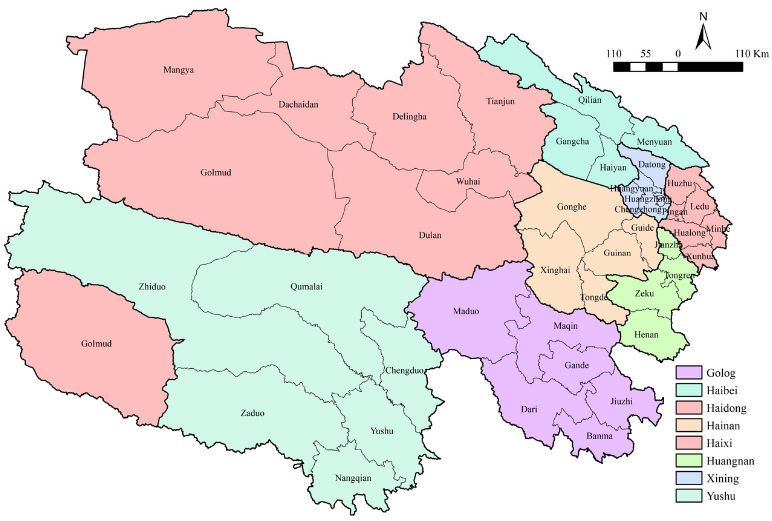


**Figure 1.** Overview of counties in Qinghai Province.

*2.2. The Study Framework*

This study proposes a framework to explore the spatial relationship between vulnerability and resilience, and the influence mechanisms of urban resilience. Based on the results, we proposed a zoning and categorized flood resilience enhancement strategy for Qinghai Province. The whole framework is shown in Figure 2.

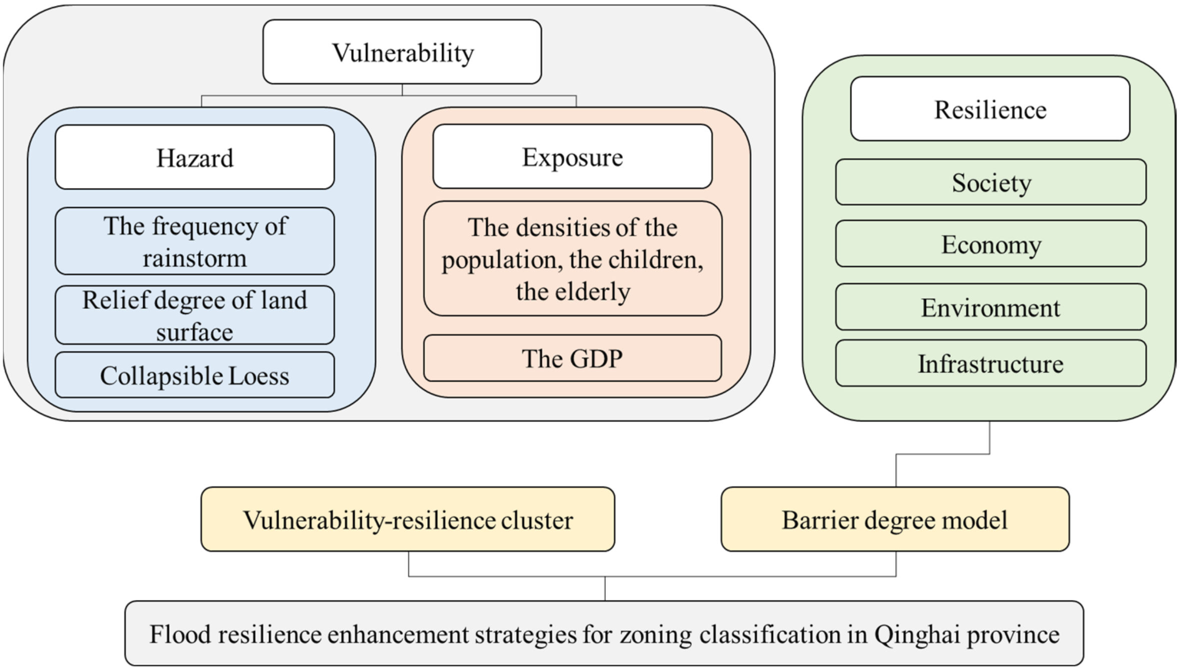


**Figure 2.** Overall study scheme.

*2.3. Methods for the Exploration of Spatial Balance between Urban Flood Vulnerability and Resilience*

2.3.1. Urban Flood Vulnerability Model

Vulnerability is commonly defined by the Third Assessment Report of IPCC as the degree of susceptibility to the damaging effects of a hazard. The vulnerability assessments focus on hazards and exposure to the socioeconomic system [36].

Rainfall is the direct factor and stimulating condition that induces heavy rainfall and flooding. The flood disaster driver index includes the amount of rainfall and frequency of rainstorms. Pearson's correlation calculations found a strong correlation exists between annual precipitation and the frequency of rainstorms. Flooding in Qinghai is mainly caused by persistent precipitation or short-term heavy precipitation, so the number of days with different intensities of precipitation is used to analyze the flooding causative factors. Therefore, the frequency of rainstorms was used in the study. Based on the meteorological disaster standards of Qinghai Province and previous studies [37], the risk grades of rainstorms and flood disasters were used to represent the factor of frequency of rainstorms. Topography is one of the key factors directly related to regional flooding. Plain areas may be flooded earlier due to the rapid flow of water from the highlands to low-lying areas [38,39]. Specifically, the Relief Degree of Land Surface (RDLS) applies the changes in altitude in a certain area to indicate the topography. The higher the RDLS, the more waterlogging and flooding are expected to occur. Collapsibility of loess is a significant factor affecting engineering construction in loess areas [40], and it can exacerbate flood disasters. Thus, this study selects frequency of rainstorms, RDLS, and collapsible loess as indicators to reflect hazards in urban planning.

Exposure can be defined as the proximity of people, property, or other elements to a hazardous area and thus suffering potential losses in any disaster [41]. In other words, exposure is the extent to which a city is plagued by catastrophic stresses. Assessment of exposure includes the number and types of people or assets exposed to a disaster. When waterlogging occurs, high population density tends to be more vulnerable to disasters. Furthermore, there is a greater chance that vulnerable populations—such as children and the elderly—will have a lower capacity to deal with urban flooding [42,43]. On the economic side, the higher the gross domestic product (GDP), the more economic damage from flooding an area will suffer. Finally, the densities of the population, the children, the elderly, and the GDP are selected as indicators to reflect the exposure to urban flooding in the area of interest.

#### 2.3.2. Urban Flood Resilience Model

Resilience is the ability to withstand, absorb, or recover from a shock and adapt to environmental stresses such as extreme flooding [44]. According to previous studies [45,46], factors representing urban resilience can be divided into four dimensions: society, economy, environment, and infrastructure.

When selecting social resilience indicators, residents' awareness of waterlogging disasters and emergency resources are important factors to consider in urban adaptability measurements [47]. It is widely accepted that those with higher educational levels are more likely to have a high capacity for learning and innovation, as well as to be more scientific and efficient in handling disasters [48]. Health facilities are key factors in reducing the impact of disasters by reducing fatal losses through adequate and timely treatment [49]. The quantity of health facilities available, like hospital beds, can be used to assess a facility's capacity to deal with emergencies and is thus an important factor for measuring urban social resilience [50].

The term "economic resilience" describes the capacity of the local economy to withstand shocks from without. When an event strikes an urban economic system, it can bounce back fast and reach its previous level of development, if not surpass it. The tertiary industry ratio is a crucial indication of urban economic development, and the per capita GDP of urban regions reflects the comprehensive capacity of the urban economy [22]. After floods, areas with high per capita GDP and tertiary industry ratios will have more financial resources available for rehabilitation efforts [15].

The environmental resilience indicator is conceptually related to environmental quality, which enhances the absorptive capacity of coastal surges and floods [16]. Storage and infiltration capacities are significantly impacted by the percentage of urban ecological space, which could reduce peak flood flow [51]. Stronger rainwater infiltration and flood resilience are associated with higher levels of vegetation covering and a higher proportion of blue-green space [52].

Infrastructure resilience is characterized by an area's ability to respond and recover. Indicators in this dimension reflect the quality and functionality of critical infrastructure's ability to perform efficiently and in a timely manner before, during, and after an adverse event [20]. Areas with a high road density have a stronger traffic capacity and post-disaster rescue operations [53,54]. In addition, the construction of urban water-related infrastructure, such as drainage networks and levee construction, contributes to the resilience to flood risk and reduces the strength of flooding. Therefore, nine indicators, namely, education level, the number of beds in medical institutions, per capita GDP, ratio of tertiary industry, vegetation covering, proportion of blue-green space, density of roads, density of drainage networks, and the length of levee, are selected for the evaluation of resilience.

All the above-mentioned indicators were normalized by deviation maximization method:

$$r_i(x) = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)}, \quad (1)$$

Subjective and objective weighting are the two different approaches used for the indicators. The subjective weighting is determined by subjective factors, and the qualitative data outnumber the quantitative data. The entropy approach is an objective weighing methodology capable of capturing the utility value of the index. Compared to its weight value, the subjective weighting approach is less reliable and accurate. Thus, the entropy approach was used to determine the weight index in this study. The entropy value was calculated using the following equation:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n}(1 - e_j)}, \tag{2}$$

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m} p_{ij} ln p_{ij}, \tag{3}$$

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, \tag{4}$$

where $e_j$ is the the entropy of the $j$th criterion,$p_{ij}$ is the normalized value of the $i$th alternative for the $j$th criterion, $w_j$ is the weight of the index $j$, $m$ is the number of indicators.

#### 2.3.3. Identifying the Relationship of Vulnerability and Resilience

Z-scores are standard scores which represent the number of standard deviations a score is above or below the mean outcome score [55]. By standardising the distribution, comparisons can be made across different variables [55]. In the specific context of resilience and vulnerability analysis, the values of vulnerability and resilience were normalized by Z-score, and the standardized values of vulnerability and resilience were characterized on the X and Y axes, respectively, and divided into four quadrants (I, II, III, and IV). Quadrants I, II, III, and IV represent different types of zoning, such as high vulnerability–high resilience, low vulnerability–high resilience, low vulnerability–low resilience, and high vulnerability–low resilience, respectively. Such insights are instrumental in informing targeted management strategies tailored to the specific challenges and opportunities posed by different resilience-vulnerability profiles. The Z-score was calculated using the following equation:

$$x = \frac{x_i - \overline{x}}{s} \tag{5}$$

$$s = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2}, \tag{6}$$

where $x$ is the value of flood vulnerability or resiliece; $\overline{x}$ is the mean value of the sample of the indicator; s is the standard deviation of the sample of the indicator; $n$ is the number of counties.

According to the Z-score, the flood vulnerability and resilience of different counties were combined, and these combinations are clustered into four groups, as shown in Table 1. People living in the high–high cluster have enough resources for adaptability. People in the high–low cluster lack adequate resources for adaptation and are at risk from urban flooding. While the areas in the low–high cluster are not particularly vulnerable to urban floods, the residents possess an abundance of resources for adaptation. People in low–low clusters are able to adjust to urban floods on their own since there is no risk of flooding there.

**Table 1.** Clusters of combinations of vulnerability and resilience.

| Flood Vulnerability | Flood Resilience | Combination | Classify |
|---|---|---|---|
| ≥0 | ≥0 | High–High | Self-adaptive |
| ≥0 | ≤0 | High–Low | Deficient in terms of nature–nurture |
| ≤0 | ≥0 | Low–High | Over-abundant |
| ≤0 | ≤0 | Low–Low | Self-adaptive |

### 2.4. Analysis of Obstacle Factors

Urban flood resilience is affected by society, economics, ecology, and infrastructure, and it is often difficult to consider all aspects when managing and making decisions on urban flood resilience enhancement because of limited resources. This study introduces an obstacle factor analysis to analyze and summarize the key factors impeding the improvement of urban resilience, allowing corresponding policy suggestions to be made for the improvement of various counties in Qinghai Province. In this way, prefecture-level cities can handle the urban issues brought on by waterlogging disasters, increase their regional comprehensive competitiveness, and accomplish sustainable development, improving the current state of regional urban resilience. The formula used to calculate the obstacle degree of urban resilience is expressed as follows:

$$m_j = \frac{W_j \times P_j}{\sum_{j=1}^{n} \left( W_j \times P_j \right)} \times 100\%, \tag{7}$$

$$P_j = 1 - Y_j, \tag{8}$$

where $m_j$ is the degree of obstacle of urban resilience index; $j$ represents the influence value of resilience evaluation index $j$ on the regional urban resilience level; $W_j$ is the weight of urban resilience index $j$; $P_j$ is the index deviation degree and represents the difference between an urban area's resilience evaluation index factor and the total resilience of the regional urban area; $Y_j$ is the normalized value of resilience index $j$.

### 2.5. Data Source

For the comprehensive consideration of the concept of vulnerability and resilience, seven indicators were developed from two categories of hazard and exposure, and nine indicators were developed from four categories: society, economy, environment, and infrastructure. The data sources of the evaluation index system are shown in Table 2. In this study, primary data related to hazards, exposure, and resilience were collected from 45 counties through field surveys. These data are mainly government statistics, including social, economic, and urban construction data. RDLS and Proportion of blue-green space were statistically obtained based on the collected geospatial data. In addition, some of the data were accounted for with reference to related studies in Qinghai Province, e.g., frequency of rainstorms. All raw data values were converted to comparable scales using percentages, per capita, etc. [39]. Since our variables were defined in a variety of statistical units, ranges, and scales in order to create and compute indices, these standardization techniques were crucial. Finally, ArcGIS version 10.4 was used to develop maps showing flood vulnerability and resilience in the study area.

**Table 2.** Indicators and data source of urban flood vulnerability and resilience.

| Component | Criterion Layer | Indicator | Data Source |
| --- | --- | --- | --- |
| Urban vulnerability | Hazard | Frequency of rainstorm | Calculated based on daily precipitation from the China Meteorological Data Sharing Service System (http://data.cma.cn/site/index.html (accessed on 20 October 2023)). |
| | | RDLS | Calculated using digital elevation model (DEM) data with 12.5 m spatial resolution from ALOS (Advanced Land Observing Satellite) (https://search.asf.alaska.edu/#/ (accessed on 21 October 2023)). |
| | | Collapsible loess | The map of collapsible loess from Qinghai Geological Data Museum |
| | Exposure | The density of the population | County Statistical Yearbook in China |
| | | The number of children | Population Census Yearbook in Qinghai |
| | | The number of elderly | Population Census Yearbook in Qinghai |
| | | GDP | County Statistical Yearbook in China |

**Table 2.** *Cont.*

| Component | Criterion Layer | Indicator | Data Source |
|---|---|---|---|
| Urban resilience | Society A | A1 Education level of people | Population Census Yearbook in Qinghai |
| | | A2 Number of beds in medical institutions | Statistical Yearbook of County Construction in China |
| | Economy B | B1 per capita GDP | County Statistical Yearbook in China |
| | | B2 Ratio of tertiary industry | County Statistical Yearbook in China |
| | Environment C | C1 Vegetation covering | Annual Report of Construction Statistics of Qinghai Province |
| | | C2 Proportion of blue-green space | Calculated by Data of the Third National Land Survey |
| | Infrastructure D | D1 Density of roads | Annual Report of Construction Statistics of Qinghai Province |
| | | D2 Density of drainage networks | Annual Report of Construction Statistics of Qinghai Province |
| | | D3 The length of levee | Annual Report of Construction Statistics of Qinghai Province |

# 3. Results

## *3.1. Urban Flood Vulnerability Assessment*

### 3.1.1. Hazard

The frequency of rainstorms, RDLS, and collapsible loess were used to evaluate the risk levels of the hazard. The spatial distribution of hazard levels is shown in Figure 3. The hazard levels were divided into four levels of very high, high, medium, and low risk by the natural intermittent method of GIS. The amounts of very high, high, medium, and low levels were 8 (18%), 8 (18%), 14 (31%), and 15 (33%) counties, respectively.

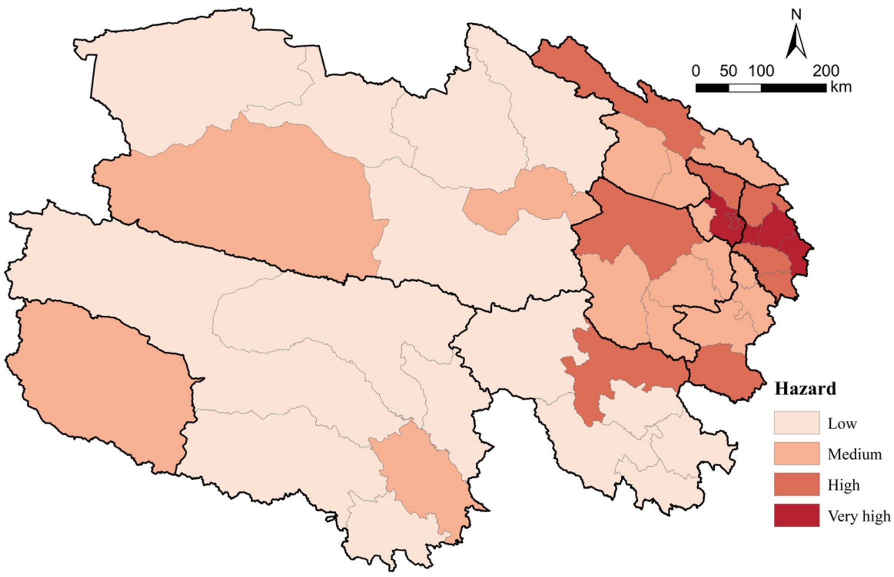


**Figure 3.** Spatial distribution of urban flooding hazard in Qinghai Province.

The areas with high levels of flooding hazard are found in the eastern of Qinghai. The eastern counties are confronted with rainstorms more frequently than the western regions due to the major influence of airflows and orographic lifting [56]. In addition, the eastern areas are mountainous, and urban areas tend to be situated in shallow river valleys, leading to severe secondary natural disasters like debris flows and landslides that occur after intense rains. Additionally, the counties with collapsible loess are mainly concentrated in the eastern portion of Qinghai Province, particularly Xining City and Haidong City. Our results are in line with the previous studies [57].

3.1.2. Exposure

The density of the population, numbers of children and the elderly, and the GDP were used to measure exposure to flooding. The risk levels of the exposure to flooding are shown in Figure 4. The numbers of very high-, high-, medium-, and low-exposure counties were 6 (13%), 11 (25%), 14 (31%), and 14 (31%), respectively.

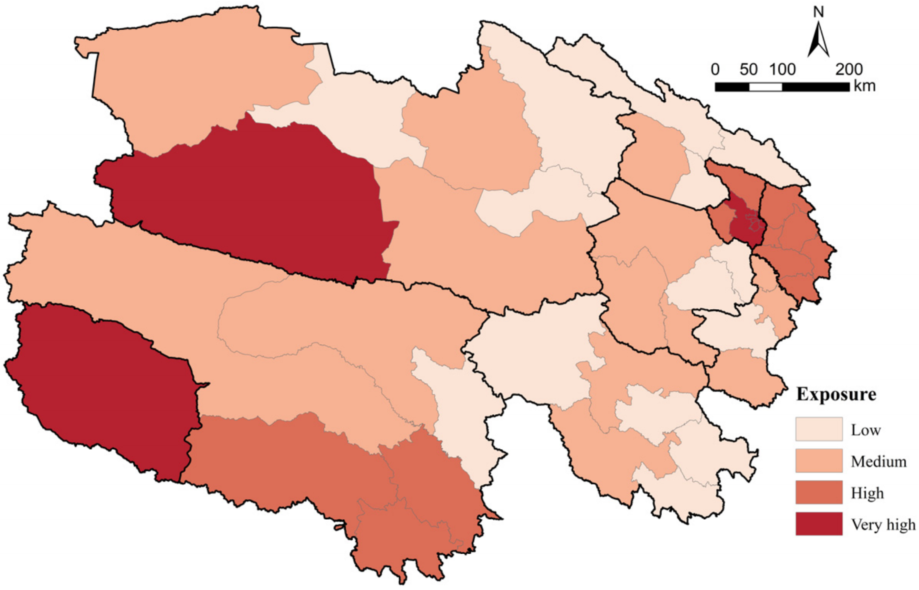


**Figure 4.** Spatial distribution of exposure to urban flooding.

In Qinghai Province, people exposed to flooding are more likely to reside in Xining and Haidong. Exposure is primarily determined by population density, which includes vulnerable populations like the elderly and children. This is because Xining and Haidong have experienced a rapid population expansion due to a large number of people moving there from other counties in Qinghai. The migration is primarily driven by two factors: (1) Xining and Haidong have good public infrastructure, including convenient public transportation, efficient schools, and hospitals; (2) there are more job opportunities, which attract many migrants who are young and generally bring their wives and children with them. Furthermore, Geermu, which experienced a very high level of exposure, has one of the highest GDPs in Qinghai. Notably, the high population density and high percentage of vulnerable population in Yushu City, as well as Zaduo and Nangqian counties in the south of Yushu Prefecture, are the primary causes of the high exposure levels in these areas.

3.1.3. The Spatial Distribution Characteristics of Vulnerability

The vulnerability level of Qinghai Province was assessed based on hazard and exposure. The spatial distribution of vulnerability levels is shown in Figure 5. The amounts of very high-, high-, medium-, and low-vulnerability counties were 5 (11%), 8 (18%), 17 (38%), and 15 (33%), respectively. Location with very high levels of vulnerability are scattered throughout Xining, which a has high hazard level and high exposure to flooding. Additionally, Yushu, Golmud, and Haidong City have a high level of vulnerability. There is no danger of flooding in the west of Qinghai.

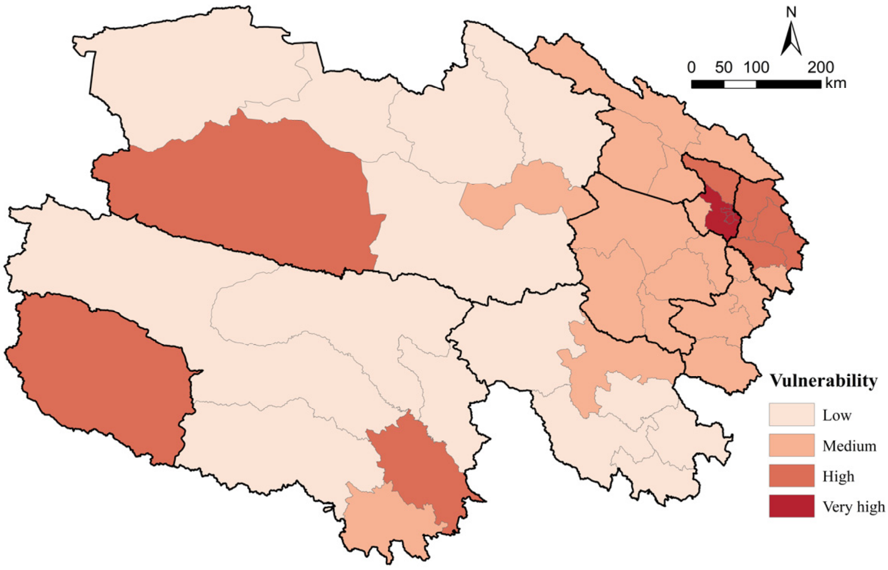


**Figure 5.** Spatial distribution of vulnerability to urban flooding.

### *3.2. Urban Flood Resilience Assessment*

The nine entropy-weighted components are summarized to assess the resilience of Qinghai. The levels of resilience to flooding are spatially demonstrated in Figure 6. In Qinghai, 33 counties (73%) have low or medium levels of resilience, most of which are accumulated in the middle and south; 4 (9%) and 8 (18%) counties have very high or high resilience levels, distributed in Xining, Haidong, and Haixi.

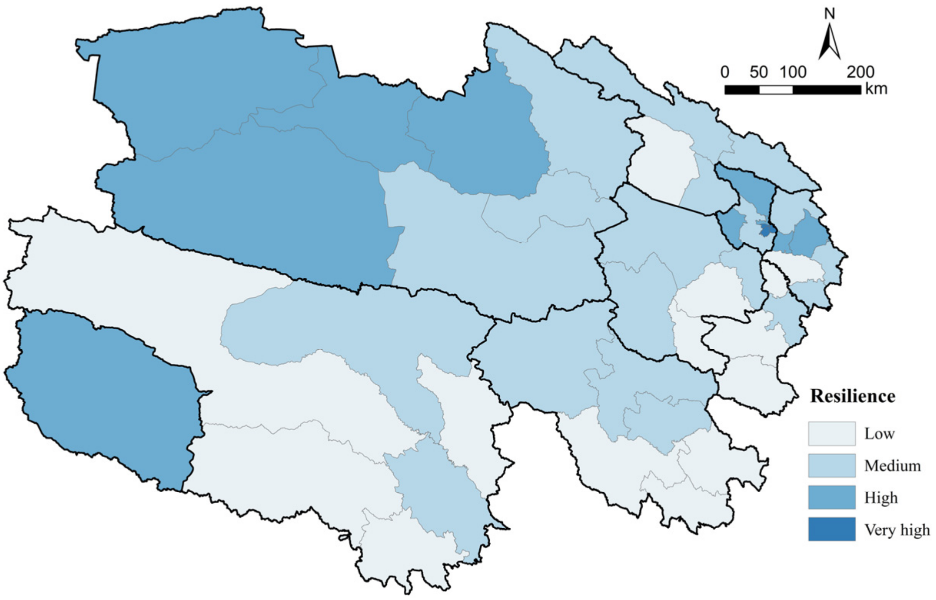


**Figure 6.** Spatial distribution of resilience to urban flooding.

Due to Xining's role as a political, economic, cultural, and commercial center in Qinghai, it has a very high level of resilience to disasters, mainly because of its good performance in infrastructure development, education levels, medical conditions, and industrial structure. Haixi has high social and economic resilience, but the construction level of drainage networks and levees is insufficient, and the comprehensive resilience of flooding is at a high level. The level of resilience in the central and southern regions of Qinghai is medium or low, mainly due to the following reasons: the low density of the road network and underdeveloped transport, which makes it impossible for medical teams and relief supplies to enter. Secondly, weak economic development makes the level of recovery from disasters less favorable.

### 3.3. Spatial Balance between Vulnerability and Resilience

This study identifies clustering patterns combined with the vulnerability and resilience to flooding. Based on four clustering patterns, three scenarios are categorized as follows: (1) self-adaptive, where vulnerability and resilience are matched; (2) over-abundant, where resources for resilience are excessive; and (3) deficient nature–nurture, where resilience is insufficient to overcome high vulnerability to flooding (Figure 7).

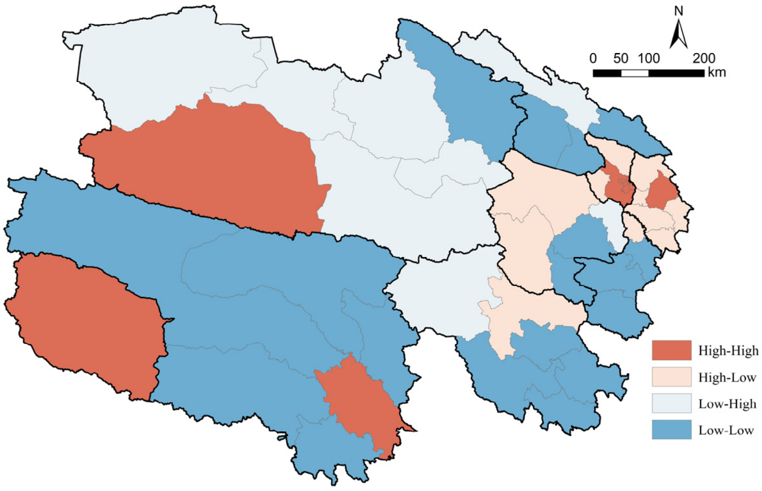


**Figure 7.** Spatial distribution of combination between vulnerability and resilience.

The spatial distribution of flood vulnerability and resilience in Qinghai is spatially unbalanced (Figure 7). The results show that 8 counties (18%) belong to the high–high cluster, and 18 counties (40%) belong to the low–low cluster. Thus, 24 counties (58%) can self-adapt to urban flooding by using resources that match their requirements. These areas can adapt to flooding hazard by using resilience resources that meet their needs, which is an ideal state for urban sustainable development. In addition, 8 counties (18%) in Qinghai belong to the low–high cluster, which has surplus flood adaptation resources, mainly concentrated in the north. Meanwhile, 11 counties (24%) in the high–low cluster have insufficient resilience resources and are hence vulnerable to flooding. Those areas are mainly distributed in the middle and east of Qinghai.

Therefore, vulnerability and adaptation resource allocation in Qinghai is spatially uneven. The majority of Qinghai Province's counties are in a state of self-adaptiveness, meaning that the resilience resources possessed by local residents match the level of flood vulnerability, and residents are able to receive timely assistance in the event of a disaster and do not suffer from a lack of resources. Several counties in Haidong and Hainan lack adaptation resources, while almost all excess adaptation resources are located in Haixi. This indicates that despite that the Chinese government playing a dominant role in adaptation resource distribution for the reduction of equity gaps [58], resources for mitigating the effects of urban flooding remain superfluous in economically well-developed areas. Thus, the methods for balancing such distributing resources must be investigated and deliberated.

### 3.4. Obstacle Factor Analysis

The primary obstacle to urban resilience in Qinghai Province is the insufficient length of flood control levees, impacting 25 counties (Figure 8). Due to the inadequate flood control infrastructure in Qinghai Province, 18 counties have yet to establish flood control levees, consequently diminishing urban resilience against rainfall and floods. Moreover, the availability of hospital beds, which rank first and second in 18 (40%) and 19 (42%) counties, respectively, emerges as the second most important factor impacting flood resilience. The reason for this is due to the fact that Qinghai Province, with the exception of Xining, has relatively low rates of urbanization and regional economic development, and the urban social security system is directly impacted by the underfunding of medical resources. The allocation of medical resources in the province is also imbalanced. The infrastructure resilience rankings for road density (D1) and drainage network density (D2) are fourth and fifth, respectively. Infrastructure has a substantial effect on resilience. Regarding economic resilience, per capita GDP (B1) is ranked third, while the percentage of tertiary industry (B2) is ranked ninth. This is mostly because agriculture dominates the urban economic structure and there is little urban development, which results in the region's overall slowly economic growth. The quantity of blue-green areas (C2) and vegetation coverage (C1) of environmental resilience have a lesser degree of resilience hurdles, typically placing seventh and eighth, respectively. In recent years, Xining has actively engaged in afforestation, ecological restoration, and tree planting, thereby enhancing the quality of the ecological environment. In other counties, there is a high rate of ecological resource preservation and a high degree of ecological resilience because of the low levels of urbanization and development [59,60].

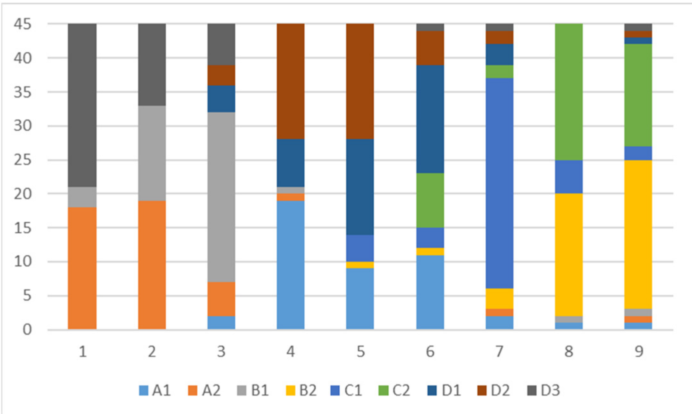


**Figure 8.** Ranking frequency of resilience indicators.

## 4. Discussion

### *4.1. Assessment of Urban Flood Vulnerability and Resilience*

Nowadays, cities are challenged by multiple external shocks (e.g., global warming) and internal pressure (e.g., urbanization and human activities) that contribute to increased flood risks [61]. Investigating cities' susceptibility to flooding and their ability to adapt and explore the spatial structure of urban flood vulnerability and resilience can lead to effective targeted urban planning to mitigate the flood risk and increase resilience. Prior researches have evaluated vulnerability and resilience to natural disasters, incorporating social, economic, and environmental factors to assess hazard risks in particular locales [62–64], with existing literature often missing concrete strategies for enhancing resilience. This study conceptualizes vulnerability to hazards and exposure and resilience to urban flooding and explores the spatial pattern between vulnerability and resilience from the perspective of spatial equilibrium. Employing a barrier degree model identifies vital factors influencing urban flood resilience. The findings offer valuable insights for refining resilience metrics and fostering interregional collaboration to strengthen resilience. Further, it suggests expanding the research scope to cover broader areas in future studies.

Scholars have explored and discussed the concepts of vulnerability and resilience in recent works [54,65]. Some scholars see resilience and vulnerability as constituent elements of each other [66], and others consider one or both of these concepts as constituent elements of broader notions such as risk [54]. Resilience, broadly defined as the ability to withstand and recover from loss, needs to address two components: the losses and the recovery process [67,68]. Losses, which include physical, economic and social dimensions, provide critical insights into the impact of hazards, such as damaged buildings, loss of assets, and affected populations. The recovery process is an integral part of efforts to build resilience. Key aspects of the recovery process include adequate financial resources, infrastructural facilities and logistical support for timely and coordinated responses. Compared to existing studies, this study proposed an assessment framework with the dimensions of hazard, exposure and resilience: (1) hazard, which is urban flooding caused by storms, including frequency and severity; (2) exposure, which is the situation of population casualties and asset losses caused by rainfall; and (3) resilience, which refers to the allocation of resources and socio-economic systems for post-disaster recovery and adaptation to urban flooding. The framework covers hazards, disaster losses and the recovery process of flooding and can inform risk assessment, promote sustainable development and enhance adaptive capacity to reduce vulnerability.

It is difficult to find a single indicator or set of indicators for measuring urban vulnerability and resilience due to the significant influence of geography and climate. In contrast to previous studies [19,69,70], the framework and indicator system of this study takes into account the unique soil and climatic conditions of the Tibetan Plateau and ensures that the indicators can be applied robustly under conditions of high altitude, extreme climate, and terrain diversity. Through collaboration with local stakeholders and professionals, this study has accessed and integrated local knowledge and experience to enrich and refine the study framework to ensure the feasibility and applicability of our approach in practice. It acknowledges the unique issue of loess collapsibility in Qinghai, which leads to structural damage like house tilting and road collapses—urgent problems in Chinese central and western areas. Under climatic humidification, the collapsibility of loess will exacerbate the flood disaster. Thus, the collapsibility of loess was considered the vulnerability factor. Furthermore, flooding disasters in Qinghai Province are caused by persistent or short-term excessive precipitation. Despite official meteorological criteria in Qinghai province (DB63/T 372-2011) [71] deeming rainstorms as events with over 50 mm of rainfall in 24 h or 30 mm in 12 h, such definitions do not align with Qinghai's flood occurrences. Therefore, this research utilizes risk grading from related studies to represent rainstorm frequency in Qinghai more accurately [37]. Our research methodology not only accurately assesses urban vulnerability and resilience in the Tibetan Plateau region, but can also provide practical recommendations and guidance for resolving regional development and sustainable management under conditions of increased flooding risk of climate change.

### *4.2. Strategies for Qinghai Province to Improve Urban Flood Resilience*

The spatial matching perspective of the vulnerability-resilience correlation exploration not only enriches our knowledge of urban flood vulnerability and resilience but also simulates practical ways to reduce the impacts of hazardous sites through urban planning, primarily through optimising the allocation of adaptation resources. This study has found spatial imbalances in the vulnerability and resilience of counties in Qinghai Province (Figure 7). Specifically, 24 counties (58%) are self-adaptive to urban flooding, 8 counties (18%) have surplus resources for flood adaptation, and 11 counties (24%) have insufficient resources for resilience and are therefore vulnerable to flooding. The disparities between counties are significant and require targeted solutions [72]. Our findings have several policy relevance for enhancing resilience in different regions to reduce the impact of urban flood vulnerability.

In self-adaptive areas, urban sustainability can be maintained through urban blue and green line control, limiting urban expansion, and protecting existing natural resources. Areas with insufficient urban resilience resources prioritize impact factors related to urban resilience, such as levee construction and allocation of healthcare resources. In summary, urban resilience can be increased through engineering and non-engineering measures.

(1) Improving the local economy is crucial to increasing counties' resilience to floods. The driving force behind the development of counties and the well-being of their inhabitants depends mainly on the local economy. Simultaneously, urban flood mitigation facilities and post-flood reconstruction efforts cannot be separated from the city's financial support.

Qinghai Province should increase the radiation-driven role of Xining's capital city to the surrounding area and promote urbanization construction and economic development.

(2) The integrated green–grey–blue (IGGB) system has gained interest worldwide in mitigating flood issues [73,74]. The IGGB urban infrastructure system for flood management should be strengthened to construct different "watershed, city, drainage zone levels". A sustainable and resilient urban environment can be created with the aid of IGGB system measures like enhancing the implementation of natural storage space and rainwater drainage channels, coordinating ecological adjustments for water conservation, optimizing the functional layout of blue and green spaces, and strategically placing grey facilities for drainage. The key to implementing an IGGB system for managing flooding is combining various technologies, including planning, water conservation, drainage, ecology, and landscape, as well as above-ground and subsurface facilities, natural space, and artificial facilities at different scales. The specialized technique of reducing urban waterlogging and establishing a habitable environment through the IGGB system is used in the construction of sponge city in China. In other words, the complete control of the total amount, peak value, frequency, and ecological and environmental pollution of urban stormwater runoff can be achieved through the comprehensive application of "green" + "blue" +" grey" engineering measures and intelligent regulation. This creates cities with the "resilience" to withstand flooding disasters.

(3) An intelligent information management platform is being built. Emerging urban planning technologies such as big data, cloud computing, artificial intelligence, mobile Internet, and so on are constantly updated while putting forward new requirements for urban flood risk management and resilience construction. In the future, counties should take urban safety technology as the core and build an integrated flood risk factor intelligent information management platform driven by interdisciplinary technology to achieve efficient and intellectual development of urban resilience management.

(4) Ecological cities are the main direction of sustainable and green development. As urban areas expand and urban populations increase, the contradiction between environmental protection and development is becoming increasingly evident. Ecological restoration of lakes, rivers, and forests in Qinghai Province should be carried out to enhance water absorption and fixation capacity during heavy rains and floods.

### *4.3. Contribution and Implication*

This study constructed the index system of spatial balance between urban flood vulnerability and resilience in Qinghai Province. The method in this study improves the shortcomings of the previous urban flood resilience assessment in index data collection, index weighting coupling, and barrier degree assessment and can effectively assess the flood resilience of various cities in Qinghai Province without losing its accuracy [75,76]. Compared with the urban flood resilience assessment framework commonly used in existing studies, it simplifies the previous complex assessment framework from pre-disaster exposure, disaster sensitivity, adaptability, and post-disaster resilience [18]. The evaluation framework with exposure, disaster, and resilience in the present study can more intuitively correspond to the resilience characteristics in the three periods before, during, and after the flood. In addition, the research scope of the existing literature mostly focuses on the comprehensive assessment results of urban-scale flood resilience [19,57]. In this study, the spatial balance between urban flood vulnerability and resilience and the degree of barrier assessment were conducted for each administrative region on the provincial scale, which was more conducive to identifying regional differences in flood resilience levels and analyzing the causes from the level of important barrier factors. This study can further expand the resilience assessment and presentation of dynamic data and can provide better guidance for the formulation of regional flood management and resilient urban planning.

Our results indicate that the number of hospital beds, the length of flood levees, and per capita GDP have significant impacts on urban flood resilience. Strengthening these aspects would assist cities both within and beyond the Qinghai–Tibetan Plateau more effectively cope with natural disasters such as floods. Other cities can also adopt corresponding methods and measures to identify the main obstacles and improve urban flood management. We believe that our research is valuable for global urban planning and disaster reduction efforts. Many countries' cities face similar natural disaster challenges, and our spatial modeling framework proposed can help identify critical vulnerable areas and formulate targeted response strategies. This framework provides a basis for the effective allocation and prioritization of adaptive resources, thereby comprehensively enhancing disaster resilience, reducing disaster losses, and promoting sustainable urban development.

## 5. Conclusions

This study investigates the spatial patterns between vulnerability and resilience and analyzes the obstacles to urban resilience using the case of Qinghai Province. The results show that the spatial inequality of resilience resources exacerbates the level of flood vulnerability in some counties of Qinghai. Therefore, the Qinghai–Tibet Plateau's distinctive urban flood mitigation solutions are given. The conclusions indicate the following: (1) The counties with high level of vulnerability are scattered throughout Xining, which has high hazard levels and exposure to flooding. The main factor contributing to the high level of hazard of the eastern counties is that these areas are mountainous, with collapsible loess and more frequent rainfall. Meanwhile, the factor contributing to exposure in the east is the combination of high GDPs and dense populations, including vulnerable groups. (2) A total of 33 counties (73%) have low or medium levels of resilience, and 4 (9%) and 8 (18%) counties have very high or high resilience levels, respectively, in Qinghai. (3) The spatial distribution of flood vulnerability and resilience in Qinghai is spatially unbalanced. The main factors affecting urban resilience in Qinghai include the number of hospital beds, the length of flood levees, and per capita GDP. Due to the active ecological restoration work in Qinghai, the environmental resilience obstacle factor is minimal. (4) Local governments follow these conclusions while constructing and preventing urban flooding. It is crucial to manage risk through engineering and non-engineering means, such as economy, ecology, IGGB system, and intelligent information management platform, in order to fully strengthen urban resilience to flooding.

Certain limitations must be addressed to enhance the quality and impact of our future work. Firstly, while this study establishes a robust framework for assessing vulnerability and resilience, it encounters constraints due to data availability, computational complexity, and the complexity of the concepts of vulnerability and resilience. The indicators may not fully reflect the level of vulnerability and resilience in the study area. Critical indicators, such as the spatial distribution of buildings and the number of emergency pumping stations within the city, which are challenging to quantify or access, were not sufficiently represented. Future research should strive to incorporate and analyze these indicators more comprehensively. Secondly, the entropy weighting method was chosen to determine the weights of the indicators, and the stakeholders were not considered. In future research, the accuracy of the model should be improved by combining expert consultation and questionnaire surveys with subjective and objective methods. Thirdly, the data processing process may cause biases in the results. For example, the distribution map of collapsible loess was obtained by manual vectorization in GIS, which may lead to inaccuracy. Additionally, the strategy proposed in this study predominantly reflects a governmental viewpoint. Subsequent research should explore the dynamics between various social actors throughout the disaster management process. It is advisable to devise enhancement strategies from the perspective of key stakeholders in urban flood management, including governments, residents, businesses, and volunteers, focusing on a collaborative approach to bolster urban resilience.

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