

Article

Assessment of Flood Risk of Residential Buildings by Using the AHP-CRITIC Method: A Case Study of the Katsushika Ward, Tokyo

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Abstract: The flood risk of urban buildings has been continuously increasing, owing to the increasing frequency and severity of floods. There is an urgent need to implement precise mitigation strategies to address the unique characteristics of urban residential structures. In this study, an indicator system consisting of 17 indicators in four dimensions (extent of hazard, degree of exposure, vulnerability, and response ability) was developed for the flood risk of residential buildings. The assessment was conducted in Katsushika Ward, Tokyo, and the ANALYTIC HIERARCHY PROCESS(AHP)—Criteria Importance Through Intercriteria Correlation (CRITIC) method was integrated with Geographic Information System(GIS) technology. The spatial distribution of residential flood risk exhibits marked heterogeneity, with ‘extremely high’ and ‘high’ risk areas concentrated in northwestern and southwestern riverine zones. These regions exhibit dense populations, substantial assets, deep immersion depths, prolonged inundation durations, high proportions of wooden houses, and narrow roads impeding rescue operations. The mitigation priorities are the following: Enhance flood-resistant building heights and quality in riverside areas, strengthen vacant house management, widen rescue access routes, promote mid-/high-rise buildings, and optimize subsidies for tenants and single-person households to minimize losses.

Keywords: flood; analytical hierarchy process; entropy weight method; GIS; flood risk assessment of residential buildings



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1. Introduction

In the context of global warming and sea-level rise, the frequency and intensity of floods in urban areas have been rapidly increasing [1–4]. Recent paradigm shifts in flood risk management, particularly exemplified by Dutch innovations in hydraulic infrastructure and adaptive planning [5–7], highlight the global urgency of addressing urban flood challenges. Factors such as shifting demographic patterns, housing degradation, inadequate flood control infrastructure, and increased economic assets contribute to an increased flood risk in future urban environments, potentially resulting in amplified losses [7–10]. Therefore, accurate disaster reduction and prevention based on urban regional characteristics has become an urgent problem for all countries.

Floods include casualties and psychological impacts, direct and indirect economic losses, building damage, the ecological environment, and resource damage [11]. Economic

losses consist of property damage, collapsed houses, and disruption of lifeline projects [10]. Notably, housing loss is the most important factor that contributes to direct loss [10,12]. Therefore, the assessment of residential flood risk holds paramount significance within the domain of flood risk analysis, representing a pivotal step in the direction of mitigating disaster risk and its ensuing repercussions [10,13].

Although a universally agreed-upon definition of disaster risk remains elusive, two widely acknowledged definitions have been proposed. (1) Disaster risk refers to the potential for adverse results or expected losses (casualties, property, livelihood, interruption of economic activities, and link damage) caused by the interaction between natural or anthropogenic disaster factors and vulnerability conditions [4,14,15]. (2) Disaster risk quantifies the level of impending or potential disasters in the forthcoming years, along with the likelihood of their occurrence [16]. Floods are recognized as a type of disaster. In this study, flood risk was defined as the product of interactions among factors driving disasters, the susceptibility of the environment, and the entities affected. This definition has led to diverse interpretations by experts across different disciplines. Some studies have assessed flood risk by considering the hazard level and vulnerability together [17,18]. Others have evaluated it by examining the hazard level, sensitivity, and vulnerability [19]. Furthermore, some researchers have investigated flood risks in terms of hazard level, exposure, vulnerability, and disaster prevention and mitigation capabilities [18].

The flood risk assessment focuses on (1) the analysis of historical floods in a specific area [20,21]; (2) risk assessment using hydrodynamic simulation techniques [22,23]; (3) risk assessment based on indicator systems or assessment frameworks [24,25]. However, it is worth noting that there is a limited body of research that focuses on assessing flood risk for residential buildings based on indicator systems. Previous studies in the field of building flood risk have predominantly focused on either the vulnerability of residential buildings to flooding [9,26,27] or the estimation of economic losses sustained by residential buildings during floods [28–37]. Moreover, research specifically addressing housing flood risks in the context of large-scale urban floods remains scarce.

- **Scale:** Urban disaster risk assessment tends to be more prevalent. However, in recent years, there have also been studies on risk assessment based on various levels of urban areas and grid classifications [9,38]. Consequently, subdivision of the area and analysis of local characteristics can more accurately implement disaster reduction and prevention strategies, strengthening the flood resistance of urban areas.
- **Indicator system:** Despite numerous proposed indicator systems, such as the Risk Index System (DDI) proposed by UNDP, the Hotspots Projects, and the Disaster Risk Management Indicator System introduced by Universidad Nacional de Colombia and the Inter-American Development Bank [24], a universally endorsed framework for risk assessment remains absent. However, the current risk assessment systems for natural disasters exhibit significant shortcomings and limited applicability to diverse regions [24]. Indicator systems for specific disasters and their assessment criteria are scarce. In addition, several indicators related to residential buildings have been proposed. Insufficient indicators suitable for the local situation are included in the indicator system, and indicator systems specific for the flood risk assessment of residential buildings are even fewer. Most indicators are qualitative, rather than quantitative.
- **Method:** The combination of qualitative and quantitative methods and the exploration of multi-source data analysis have emerged as a prevailing trend in the field [22].

Using Katsushika Ward, Tokyo, as an example, this study established an indicator system for assessing the flood risk of residential buildings in the context of large-scale floods. The ANALYTIC HIERARCHY PROCESS(AHP)—Criteria Importance Through

Intercriteria Correlation (CRITIC) method and Geographic Information System (GIS) were used to assess the flood risk of residential buildings in Katsushika Ward, Tokyo, considering hazard level, degrees of exposure, vulnerability, and response ability. As a result, the spatial distribution characteristics of flood risk for residential buildings in Katsushika Ward, Tokyo, were determined. These findings offer a fundamental framework for flood management, targeted strategies, and disaster risk mitigation.

The study area includes not only coastal areas but also inland areas widely distributed in the lowlands [39,40]. Japan's population and assets are highly concentrated in Tokyo, resulting in an increased flood risk for residential buildings in Tokyo [41]. Changes in the social economy and climate have contributed to an increase in flood risk [39]. In 2017, Japan revised the Water Prevention Law to establish a society with minimal economic loss and safe living [42,43]. In September 2020, Japan implemented the law by removing flooded areas from residence-guidance areas [44,45]. As of December 2020, this initiative has led to the identification of 345 Urban Public Residence Guidance Areas [44]. However, evaluating flood risk for residential buildings within these areas requires a nuanced understanding of the regional characteristics. This precision is crucial for the effective deployment of flood control and disaster-reduction strategies, ultimately reducing direct losses.

This study establishes a flood risk assessment framework for residential buildings in Katsushika Ward, Tokyo, by integrating the AHP-CRITIC method and GIS technology, generating spatial distribution maps of flood risk. The research novelty is manifested in three key aspects. This study focuses on a low-lying and flood-prone urban area in Tokyo, assessing the large-scale flood risks to residential buildings in Japan's densely populated metropolitan areas. The hybrid AHP-CRITIC approach synergizes quantitative and qualitative weighting mechanisms, effectively reducing subjectivity in risk assessment outcomes while balancing expert judgment with objective data correlations. The framework incorporates 17 localized indicators reflecting Tokyo's unique urban morphology, including owner-occupied population, renters, vacant properties, single-story residences, two-story residences, wooden houses, one-family houses, mid- and high-level conversion rates, narrow road segments (<4 m in width), subsidies, communal residences, and quality housing for older adults.

2. Materials and Methods

2.1. Study Area

Katsushika Ward is located at a low altitude in the east of Tokyo, Japan, at 139°50'–139°55' east longitude and 35°41'–35°48' north latitude (Figure 1). It has a total area of 34.80 km² and is one of the five eastern wards of Tokyo with a high concentration of population and assets [46]. The western part of the district is 0 m above sea level. The eastern part is between 1 m and 2.5 m above sea level and belongs to the lowland. Arakawa, Edogawa, Nakagawa, Shin Nakagawa, and Ayase rivers flow in the zone and the flood risk zone [46].

In terms of land use, housing land accounts for 95% of the total area, with the rest allocated to agricultural land and railway land. The district is characterized by densely populated blocks, predominantly composed of wooden housing, and a limited number of flood shelters, as outlined in the summary provided by Katsushika Ward. Owing to the influence of population, economy, topography, hydrology, and meteorology, this area is seriously affected by floods [40,46]. Historically, Katsushika Ward has experienced significant flood damage to residential buildings. In 1910, the Great Kanto Flood inundated 70% of Katsushika Ward, resulting in the collapse of 1200 residential buildings and damage to 8500 houses. During Typhoon Kathleen in 1947, Tokyo recorded 72,945 households affected by floor-level flooding, 56 houses completely destroyed, 8 fatalities, and 138 injuries. The 1958 Typhoon Kanogawa caused the Nakagawa River basin to overflow, flooding approx-

imately 41,500 houses and submerging 28,000 hectares of land. In June 1966, a typhoon brought 300 mm of rainfall to Tokyo and surrounding areas, severely damaging residential buildings in multiple locations. In August 1982, a typhoon led to the flooding of 1615 houses and the inundation of 360 hectares of land in the Kanto region [40,46,47]. In recent years, the flood risk of residential buildings has increased with the concentration and scale of flooding, deterioration of residential buildings, wearing of old roads and facilities, and subsidence of the ground [46]. The flood risk of residential buildings should be mitigated to improve the flood disaster prevention infrastructure. This endeavor aligns with the overarching objective of creating a residential environment that embraces distinctive regional characteristics, as indicated in Katsushika Ward's basic housing plan. Furthermore, this study focused on developing urban spaces that are resilient to smaller-scale floods, thus enabling rapid recovery and reconstruction [43,45,48,49].

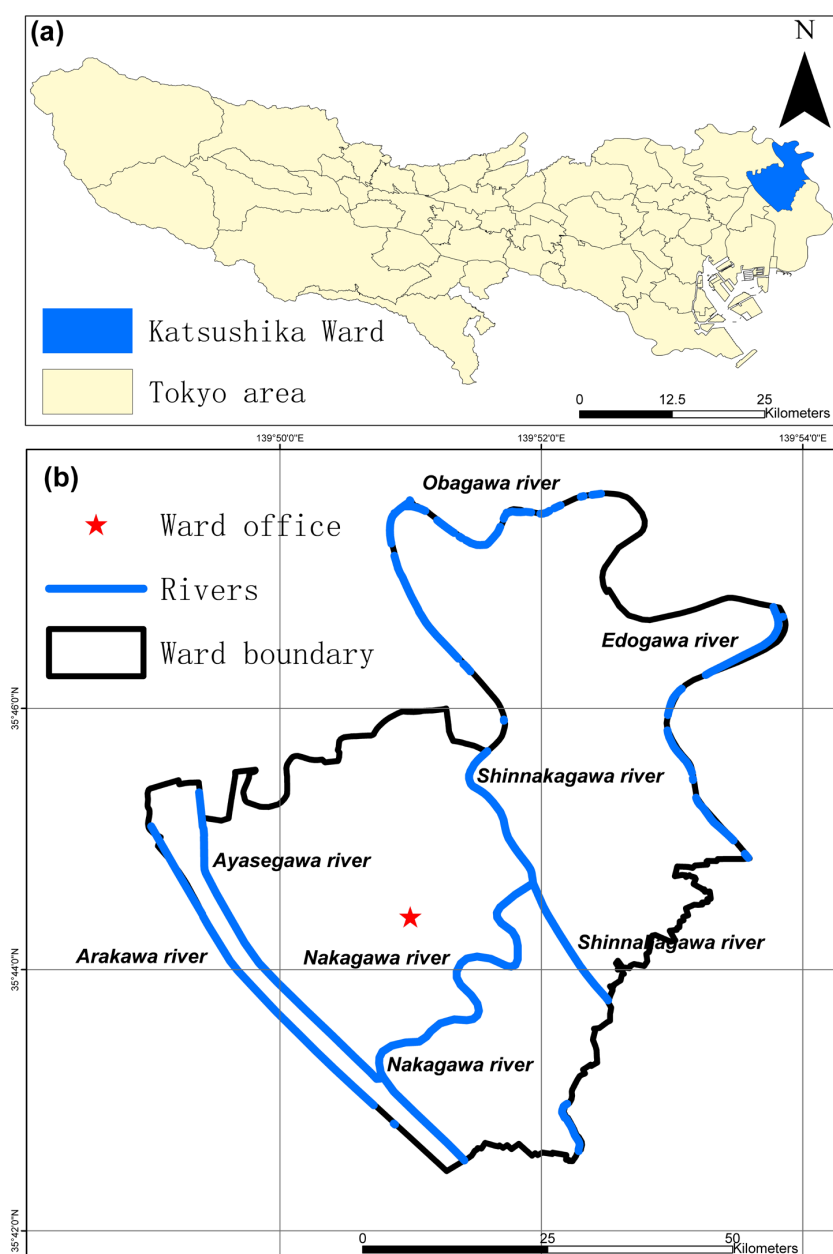


Figure 1. Study area. (a) Tokyo area; (b) Katsushika Ward.

2.2. Data Collection and Processing

2.2.1. Data Used for Research

The immersion depth and immersion duration were calculated in 2016 by the Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan. The Katsushika Ward flood map is based on the premise that floods occur once every 200 years in the Arakawa Lower basin. These data were in shapefile format with 25 m $\times$ 25 m grids.

Household population data were used for small regional populations. Small-area population data were collected from Japan's 2015 National Population Census, which included households and one-person families.

Housing-related data were extracted from Japan's 2015 National Survey's small-area population dataset, including details on residential building types, residence classifications, and ownership relationships. Based on the calculation of population data, ESRI's ArcGIS 10.6 was used to obtain one-family houses, common houses, independent houses, and rental households by area.

Wooden houses were obtained from the Katsushika Ward wood building rate [50], and ArcGIS was used to divide the 25 m grid wooden houses by area.

The subsidy data were based on the immersion depth and basic statistics of the population in Japan's 2015 National Census, including the situation of homeowners, renters, and households. Additionally, the recharge at the immersion depth was based on the revised summary based on the guidelines of the Japanese government for the identification of residential disaster victims [March 2018].

The housing land rate, medium- and high-rise conversion rate, area with roads less than 4 m in width, and quality housing for older people were obtained from the Katsushika Ward Housing Basic Plan.

The data on empty houses were obtained from other projects, such as Katsushika Ward's Empty House.

Data from one- and two-story residential buildings were obtained from Zenrin data.

2.2.2. Selection of Indicators

This study, grounded in the disaster risk system theory and informed by relevant domestic and international research, selected indicators based on principles of data availability, ease of quantification, scientific rigor, operational feasibility, and representativeness.

A flood risk assessment indicator system for residential buildings was established based on a previous risk assessment model. The AHP-CRITIC method was then adopted to combine weights and MATLAB 7.0 to obtain the flood risk of residential buildings. Furthermore, the spatial distribution of the flood risk in residential buildings in the study area was investigated using GIS.

The degree of a flooding hazard is a pivotal factor in urban flood disasters. It is affected by a variety of factors such as extreme precipitation, impervious area, low underlying surface, and flood control and drainage capacity [10]. Commonly used indicators include the immersion depth, immersion duration, and immersion speed. This study mainly analyzed the degree of flooding hazard using two indicators, immersion depth and immersion duration. When a flood occurs, the damage to residential buildings at the immersion depth is significant. Moreover, extended periods of immersion, particularly for structures such as wooden houses, may increase the risk of structural failure [42,51].

Flood exposure is a critical element of urban flood disasters and is typically assessed using indicators such as urban population, housing, and infrastructure [10]. Aiming at the flood risk assessment of residential buildings, this study selected households, land rate, rental households, and the number of owner-occupiers related to residential buildings.

Flood vulnerability is a vulnerability receptor in urban flood disasters. Commonly used indicators include women, older adults, children, individuals with disabilities, and those in marginalized economic situations. To evaluate the flood risk of residential buildings, indicators related to residential buildings were selected. One-person family, empty properties, one-story and two-story residential buildings, wooden houses (households), and one-family houses (households). In a flood event, the damage to a house that is deeply immersed in water is substantial. Moreover, if flooding lasts for a long period, the construction of houses, such as wooden houses, may be in danger of collapse [42,51].

Flood prevention and mitigation capability refers to the pre-disaster prevention and post-disaster recovery capabilities of affected areas in the face of flood disasters [18]. Commonly used indicators are the density of shelters, the density of medical care, the number of rescue vessels, GDP per capita, and fiscal revenue. Aiming at the flood risk assessment of residential buildings, this study selected indicators related to residential buildings, such as the rate of high-rise conversion, area with roads less than 4 m in width, subsidies, household composition, and provision of quality housing for older adults. High-rise residential buildings, particularly those with elevated floors, exhibit enhanced flood-control capabilities [11,12,42]. Residences located near narrower roads corresponded to lower depths of immersion, thereby increasing the flood risk for the house. Furthermore, these houses pose challenges to post-disaster repair efforts, including restricted access to construction vehicles [42]. Efforts aimed at enhancing flood control capabilities for economically disadvantaged individuals, including common houses and high-quality housing for older people, serve to alleviate challenges in the rescue and reconstruction processes. Moreover, the degree of post-disaster subsidies allocated to damaged houses directly corresponds to increased flood control and disaster reduction capacities, thus mitigating flood risk for residential buildings (Table 1).

Table 1. Descriptions of indicators.

Module	Index Code	Index	Explanation	Index Property
Extent of hazard	H1	immersion depth (m)	Greater the immersion depth corresponds to higher flood risk for houses [51].	+
	H2	immersion duration (hr)	Longer immersion duration is associated with increased flood risk for houses [52].	+
Exposure	E1	Household (number)	Higher population levels are linked to elevated flood risk [10]	+
	E2	Homestead rate	Increased homestead rates lead to greater flood risk [42]	+
	E3	Rental households (number)	A higher number of tenants increases flood risk [42].	+
	E4	Home ownership population (number)	Larger populations of self-owned houses result in greater flood risk for houses [42].	+
Susceptibility	S1	one-person family (number)	A higher presence of one-person families is connected to heightened flood risk [42].	+
	S2	empty house (number)	A greater number of empty houses is linked to increased flood risk [42].	−
	S3	one-story residential building (number)	The presence of more one-story residential buildings corresponds to higher flood risk [17]	+
	S4	two-story residential building (number)	A larger number of two-story residential buildings is associated with increased flood risk [17].	+
	S5	wooden houses (number)	An increased number of wooden houses leads to greater flood risk [10,21]	+
	S6	one-family house (number)	A higher prevalence of one-family houses is connected to increased flood risk [53]	+

Table 1. Cont.

Module	Index Code	Index	Explanation	Index Property
Lack of Resilience	LoR1	Mid—and high-level conversion rate	A greater rate of high-rise buildings corresponds to increased flood risk [10,21]	—
	LoR2	Area with roads less than 4 m in width (m ²)	A larger area with roads less than 4 m in width is linked to higher flood risk [42].	+
	LoR3	Subsidies (10,000 yen)	Increased grants availability is associated with reduced flood risk [54].	—
	LoR4	Common house (household)	A higher prevalence of common homes results in reduced flood risk [55].	—
	LoR5	Quality housing for older adults (number)	An increased number of high-quality houses for older adults is linked to reduced flood risk [55].	—

‘+’ indicates an increase in vulnerability, and ‘—’ indicates a decrease in vulnerability.

2.2.3. Establishment of Matrix

- Criteria Importance Through Intercriteria Correlation Method (CRITIC)

The Criteria Importance Through Intercriteria Correlation (CRITIC) method is an improvement of the entropy weight method. It determines objective weights by evaluating the contrast strengths and conflicts among indicators, thereby enhancing the accuracy and comprehensiveness of weighting results [56].

Before the calculation, the maximum and minimum value methods were employed to normalize the influencing factors to eliminate the impacts of different units on data comparison. Based on data normalization, the correlation coefficient of the index was calculated as follows:

For positive indicators, the following formula was used for standardization:

$$y_{ij} = \left(x_{ij} - \min_{1 \leq i \leq n} x_{ij} \right) / \left(\max_{1 \leq i \leq n} x_{ij} - \min_{1 \leq i \leq n} x_{ij} \right) \quad (1)$$

For negative indicators, the following formula was used for standardization:

$$y_{ij} = \left(\max_{1 \leq i \leq n} x_{ij} - x_{ij} \right) / \left(\max_{1 \leq i \leq n} x_{ij} - \min_{1 \leq i \leq n} x_{ij} \right) \quad (2)$$

where $i = 1, 2, 3, \dots, n$; $j = 1, 2, 3, \dots, m$; $\max_{1 \leq i \leq n} x_{ij}$ is the maximum value of the j -th indicator; and $\min_{1 \leq i \leq n} x_{ij}$ is the minimum value of j . After standardization, all values were within the range $[0, 1]$. The closer the value is to 1, the greater the positive contribution to flood resilience; conversely, the smaller the negative value.

On the basis of data normalization, the correlation coefficient r_{xy} is

$$r_{xy} = \text{cov}(x, y) / \sqrt{\text{var}x \text{ var}y} \quad (3)$$

where $\text{var}x$ and $\text{var}y$ are variances of x and y , respectively; and $\text{cov}(x, y)$ is the co-variance of x and y .

The quantization result f_j of the conflict between the j -th indicator and other m evaluation indicators is calculated using the following equation:

$$f_j = \sum_{i=1}^m (1 - r_{xy}) \quad (4)$$

The amount of information c_j contained in the j -th indicator is calculated as follows:

$$c_j = \delta_j \sum_{i=1}^m (1 - r_{xy}) \quad (5)$$

where δ_j is the standard deviation of the j -th indicator.

The weight of the j -th indicator (w_j^1) can be calculated by

$$w_j^1 = c_j / \sum c_j \quad (6)$$

- Analytical hierarchy process (AHP)

AHP was developed by the University of Pittsburgh in the early 1970s [57]. It involves decomposing complex problems into several levels and factors. Importance scores are subsequently assigned to the evaluation indicators by experts based on their expertise. A judgment matrix is then constructed according to the scoring results, and the importance of the elements at each level is analyzed using mathematical methods. The weight of the evaluation index is calculated and obtained after the consistency test, which can be regarded as a subjective weighting method [58]. This study underwent a consistency check, with the CR of the judgment matrices for Extent of hazard, Exposure, Susceptibility, and Lack of Resilience being <0.1 , indicating that the matrices have good consistency.

- Combinatorial weighting

To mitigate the limitations of the CRITIC method and enhance the accuracy of the weight determination, this study integrated the strengths of both the CRITIC method and AHP. This was achieved through a combined weighting approach, in which the weights obtained from both methods were integrated. The reference formula is as follows:

The Lagrange multiplier method can be applied to solve the constrained function, and the combined weight of the evaluation index is the value of the subjective and objective weight couplings. The combined weight W_j can be obtained by solving the optimization problem according to the Lagrange multiplier method, i.e.,

$$W_j = \sqrt{w_j^1 w_j^2} / \sum_{j=1}^n w_j^1 w_j^2 \quad (7)$$

where w_j^1 is the weight obtained using the entropy weight method; w_j^2 is the weight obtained using AHP; and W_j is the weight after combinatorial weighting.

After calculating the total value for each hazard, the degree of exposure, vulnerability, and response ability, the flood risk value of residential buildings was determined by the definition of flood risk. R is the flood risk of residential buildings, H is the hazard value, E is the exposure value, V is the vulnerability value, and C is the response ability value. The formula is as follows:

$$R = H \times E \times V \div C \quad (8)$$

Establishing a universal standard for determining the flood risk levels of residential buildings remains challenging. Numerous studies have been conducted to determine this using natural classification methods. This study employed a natural classification method to categorize the flood risk levels into five distinct tiers. To effectively represent the degree of hazard, exposure, vulnerability, and response ability within the flood risk assessment, each level was determined using the same natural classification method (Figure 2).

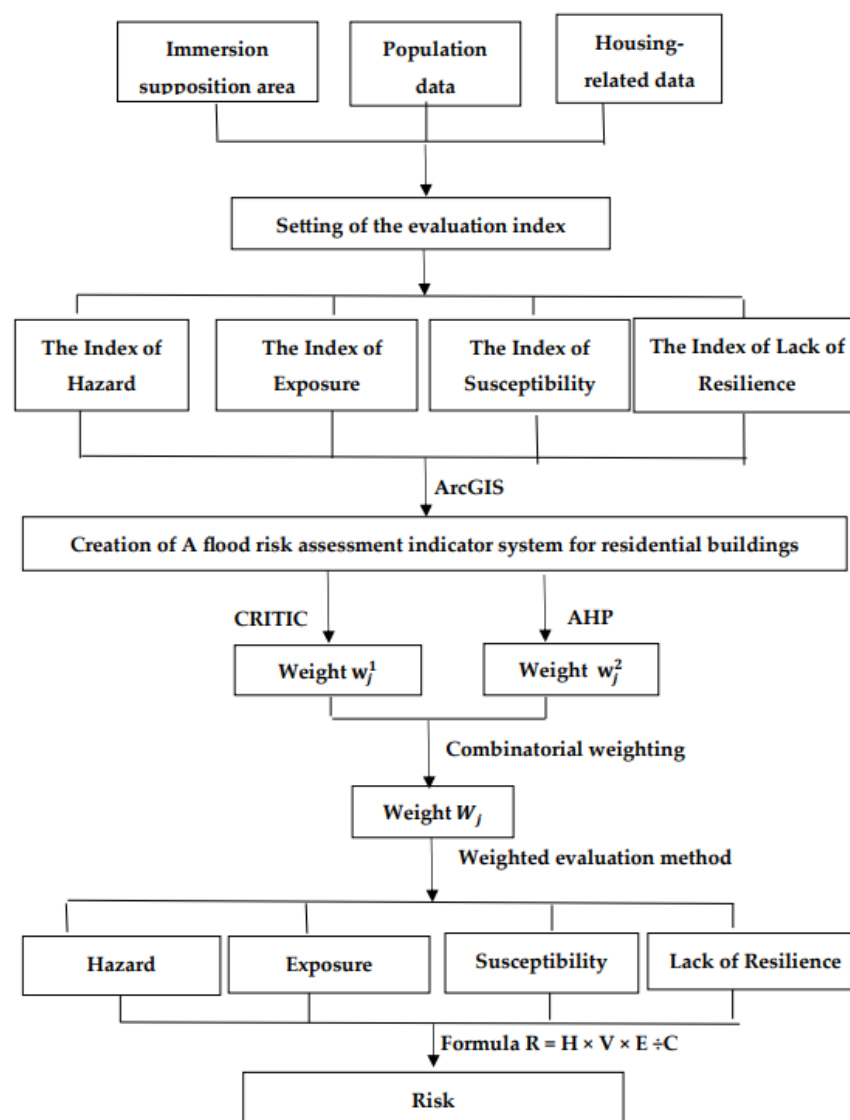


Figure 2. Flow diagram of A flood risk assessment indicator system for residential buildings model.

2.3. Evaluation Grading

To clearly demonstrate the results, the assessment results for the flood risk of residential buildings, as well as the degrees of hazard, exposure, vulnerability, and response ability, were classified into five distinct categories: high, high, medium, low, and low. This classification was achieved by applying the optimal natural breakpoint classification method in ArcGIS 10.7.

3. Results

The weights of each index obtained from the combination of the weights are listed in Table 2. Based on the four dimensions of flood risk of residential buildings as the assessment project (degree of hazard, degree of exposure, vulnerability, and response ability is significant in the assessment of flood risk of residential buildings. The other dimensions are the degree of exposure and the degree of hazard, in that order of importance.

Table 2. Weight of each index.

Module	Index Code	Index	w_j^1	w_j^2	W_j
Extent of hazard	H1	immersion depth (m)	0.0698	0.1939	0.1253
	H2	immersion duration (hr)	0.1385	0.0561	0.0943
Exposure	E1	Household (number)	0.0506	0.1265	0.086
	E2	Homestead rate	0.0738	0.0553	0.0687
	E3	Rental households (number)	0.0463	0.0437	0.0481
	E4	Home ownership population (number)	0.0468	0.025	0.0367
Susceptibility	S1	one-person family (number)	0.0469	0.0611	0.057
	S2	empty house (number)	0.0706	0.0773	0.083
	S3	one-story residential building (number)	0.0105	0.0372	0.0212
	S4	two-story residential building (number)	0.0238	0.027	0.0272
	S5	wooden houses (number)	0.0652	0.0193	0.0371
	S6	one-family house (number)	0.0553	0.028	0.0423
Lack of Resilience	LoR1	Mid—and high-level conversion rate	0.0771	0.0752	0.0816
	LoR2	Area with roads less than 4 m in width (m ²)	0.1005	0.0749	0.0931
	LoR3	Subsidies (10,000 yen)	0.0722	0.0304	0.0502
	LoR4	Common house (household)	0.0496	0.0315	0.0423
	LoR5	Quality housing for older people (number)	0.00248	0.0376	0.0102

In terms of indicators, immersion depth, immersion duration, and roads narrower than 4 m were the most significant, followed by factors such as the number of families, rate of middle and high-rise development, and household count. Additionally, empty houses have relatively high weights, whereas the weights of two-story and one-story residential buildings are low.

Figure 3 shows the distribution of the flood hazard degree for residential buildings in the study area. This hazard assessment integrated immersion depth and duration. Figure 3a illustrates the immersion depth distribution, with high levels predominantly in the northwest and low levels in the eastern part. Figure 3b shows the distribution of immersion duration, with longer durations in the west than in the east, particularly in the central and southern regions. Figure 3c illustrates the overall flood hazard degree for residential buildings. Residential buildings with high flood hazard levels were mainly identified in the west, with notable concentrations near the central area. Residential buildings with a high degree of flood hazard were discovered mainly in the eastern part.

Figure 4 illustrates the spatial distribution of flood exposure in residential buildings in the study area. This assessment combines four key indicators: household count, homestead rate, rental occupancy, and owner-occupied population (number). Figure 4a provides the distribution of the number of families. Family households are more prevalent in the western region and are densely concentrated in the southwest. Figure 4b displays the spatial distribution of homestead rates, with high rates concentrated in the northwest and southeast. Low rates were observed along the riverbanks in the northeast and southwest regions. Additionally, Figure 4c illustrates the distribution of rental households, which are predominantly located in the western and southeastern regions, with partial concentrations in the northwest and southwest regions. The population distribution of home ownership is shown in Figure 4d. The southern part of the study area exhibited a high concentration of owner-occupied households, whereas the northeastern and riverside areas had a low proportion of owner-occupied residents. Furthermore, Figure 4e illustrates the degree of exposure of residential buildings to flooding, revealing widespread high exposure levels in areas characterized by high residential exposure, particularly in the western and

southeastern sectors. Conversely, low exposure levels were predominantly found in the eastern coastal areas.

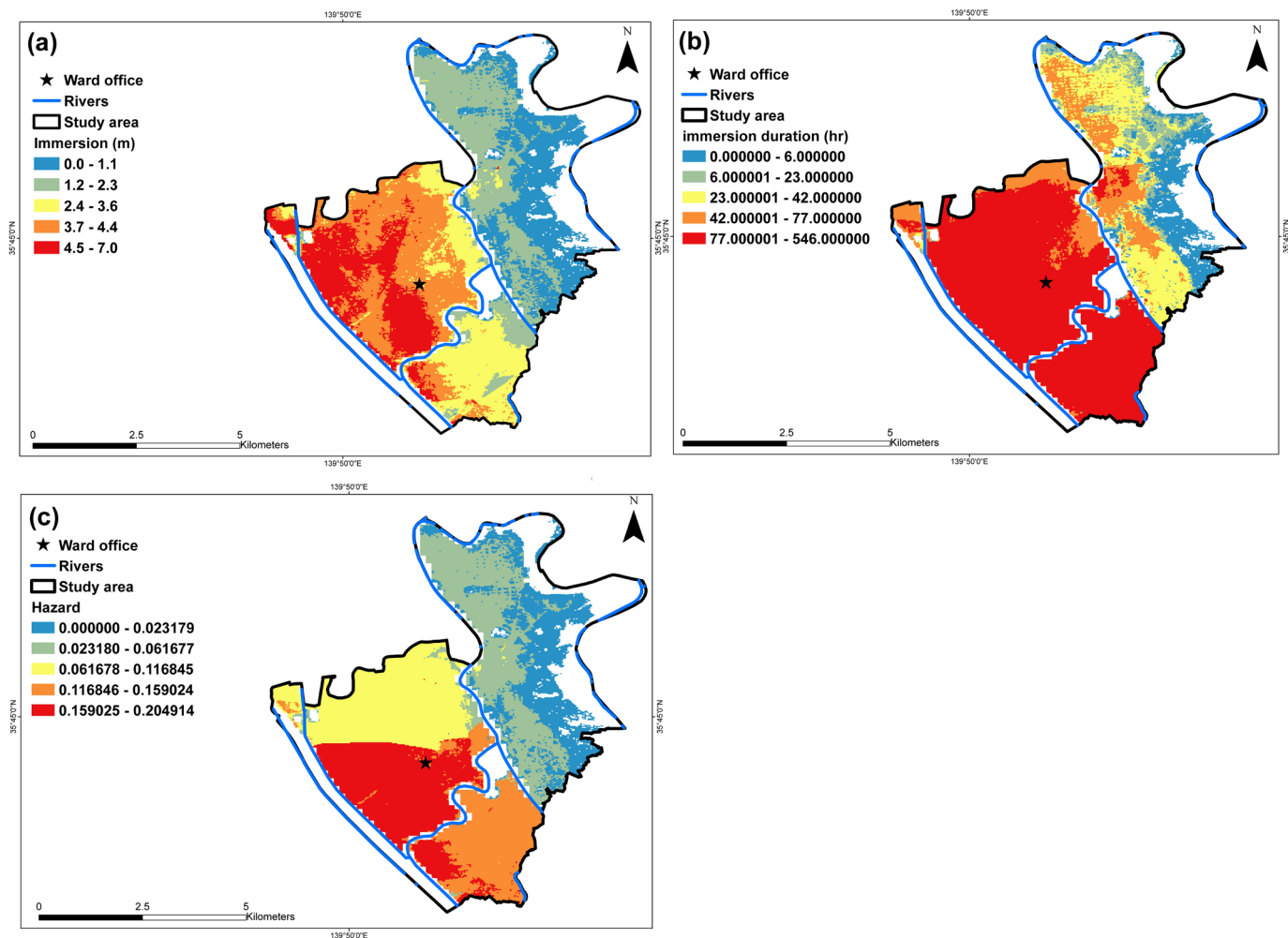


Figure 3. Flood hazard degree for residential buildings. (a) Distribution of immersion depth; (b) immersion duration distribution; (c) distribution of degree of hazard of residential buildings to flood.

Figure 5 illustrates the flood vulnerability of residential buildings within the study area. The vulnerability assessment was based on six key indicators: one-person households, vacant properties, single-story residential buildings, two-story residential buildings, wooden houses, and one-family houses. Figure 5a shows the detailed distributions of these indicators. One-person households were primarily concentrated in the southeastern and western regions, whereas they were less prevalent in the northeastern and riverside areas. Vacant houses are predominantly situated in the southern region, with rare occurrences in the northeast (Figure 5b). Single-story residential buildings were mainly located in the northwest, southwest, and northeast (Figure 5c). Two-story residential structures are widely dispersed in the northwest and southeast regions (Figure 5d). Wooden houses were identified in the southwestern and eastern regions (Figure 5e). One-family households were abundant in both the western and eastern regions but were less distributed in the central and riverside areas (Figure 5f). Figure 5g illustrates the spatial distribution of the vulnerability of residential buildings to floods. High vulnerability was widespread, with notable concentrations in the southeastern, central northwestern, and southwestern zones. Conversely, low vulnerability was primarily situated in the northwest.

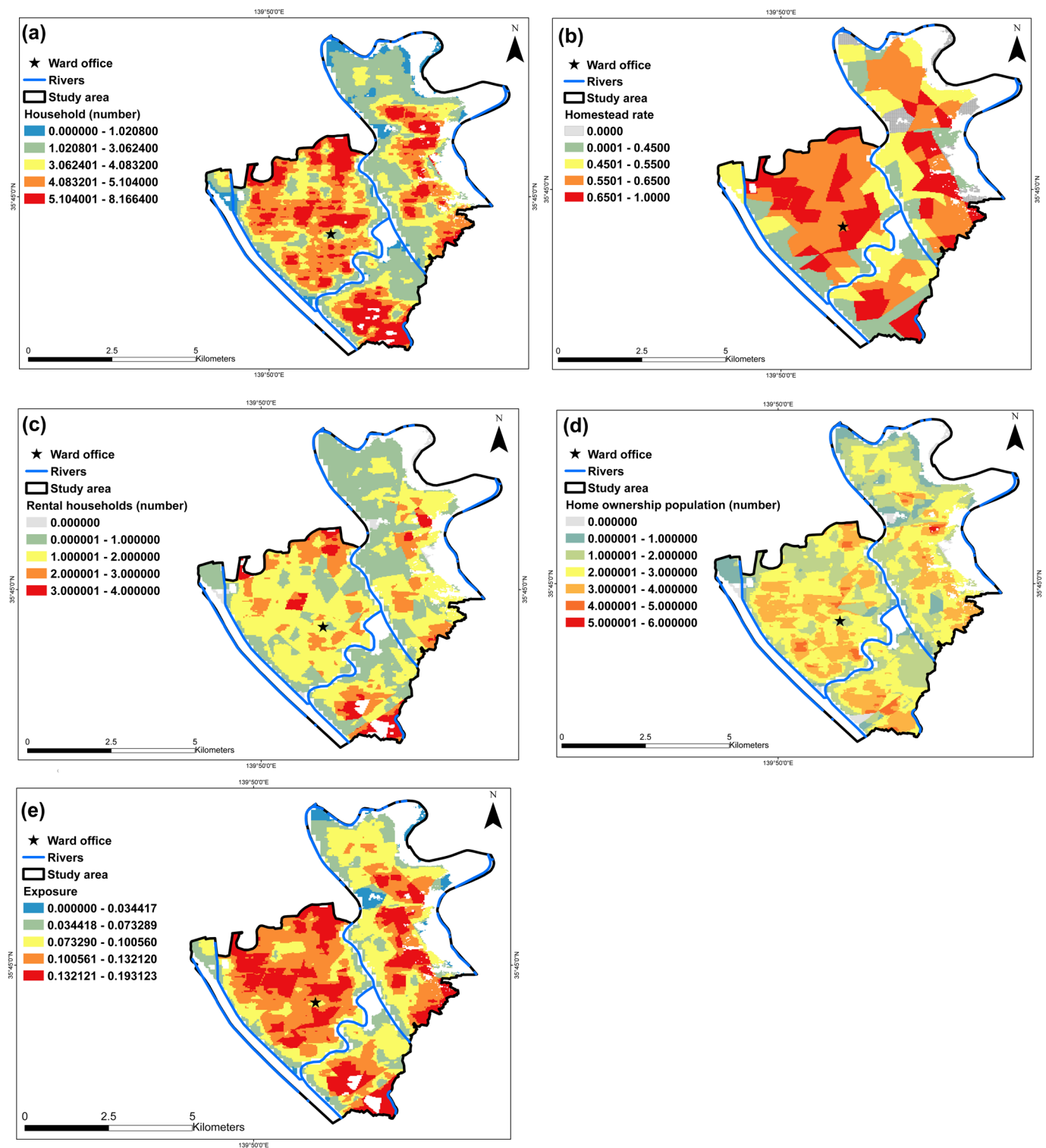


Figure 4. Exposure degree for residential buildings to flood. (a) Household distribution; (b) home-
stead rate distribution; (c) distribution of renters; (d) distribution of home ownership population;
(e) distribution of degree of exposure of residential buildings to flood.

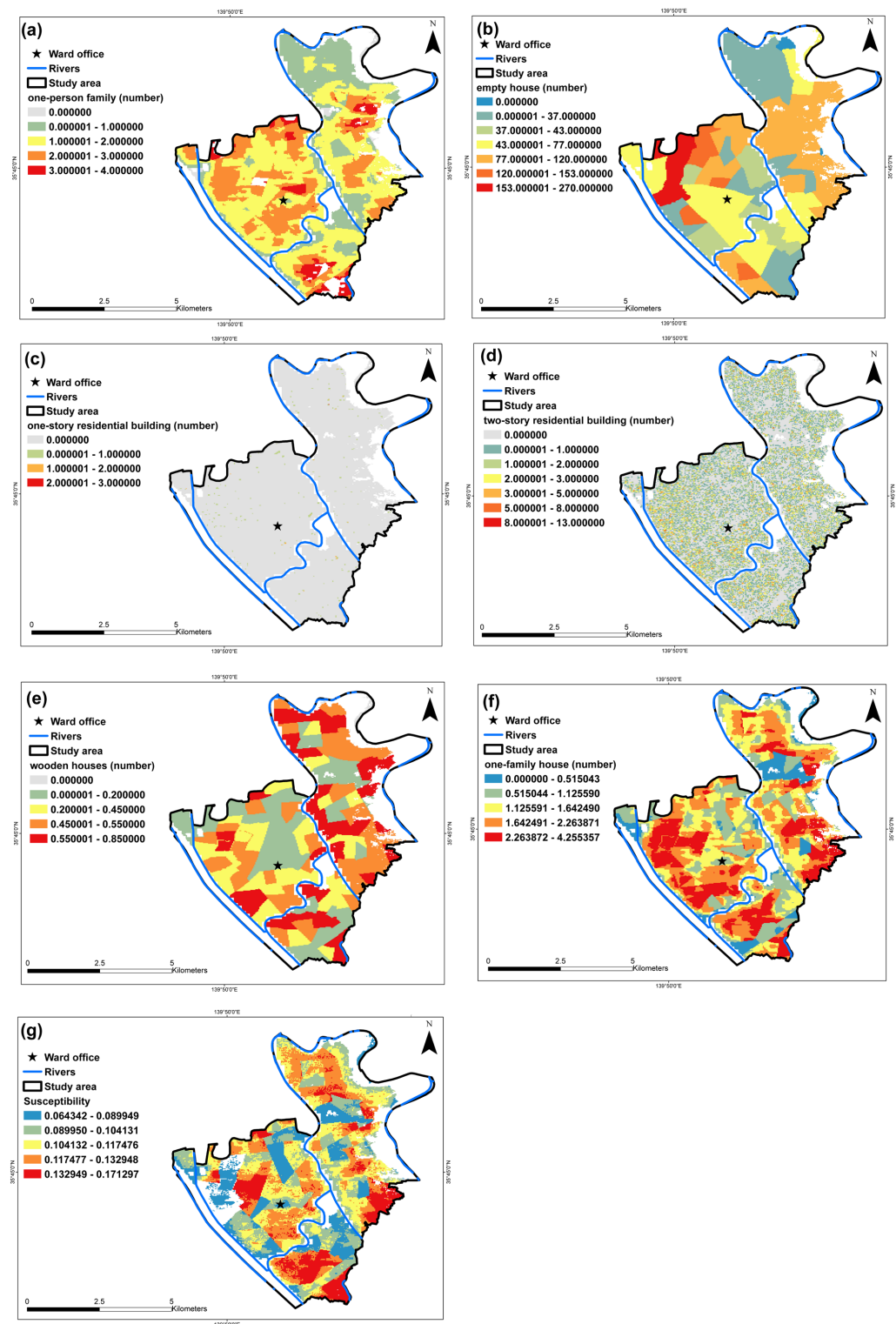


Figure 5. Vulnerability of residential buildings to floods. (a) Distribution of one-person family; (b) distribution of empty house; (c) distribution of one-story residential building; (d) distribution of two-story residential building; (e) distribution of wooden houses; (f) distribution of one-family house; (g) distribution of vulnerability of residential buildings to flood.

Figure 6 depicts the spatial distribution of the residential building response capacity to flooding within the study area. This response capacity was determined by evaluating five key indicators: the rate of medium- and high-rise development, the presence of roads less than 4 m in width, subsidies, common household composition, and quality housing

for older adults. Figure 6a illustrates the distribution of medium- and high-rise development rates, which are primarily concentrated in the northwest, southwest, and northeast regions. Additionally, areas with roads narrower than 4 m are predominantly situated on the western riverside and southeastern areas, as illustrated in Figure 6b. Figure 6c illustrates the distribution of subsidies, with a concentration in the western region and sparse allocation in the east. Similarly, Figure 6b provides insights into the distribution of common housing, which is most prevalent in the central and southwestern regions and sparse in the northeast. Moreover, high-quality housing for older people is more common in the north and remarkably scarce in the southwest, as highlighted in Figure 6e. Figure 6f shows the response capacity of residential buildings to flooding. High and extremely high response capacities were predominantly observed along the eastern and western riversides, whereas lower response capacities were primarily located in the western area.

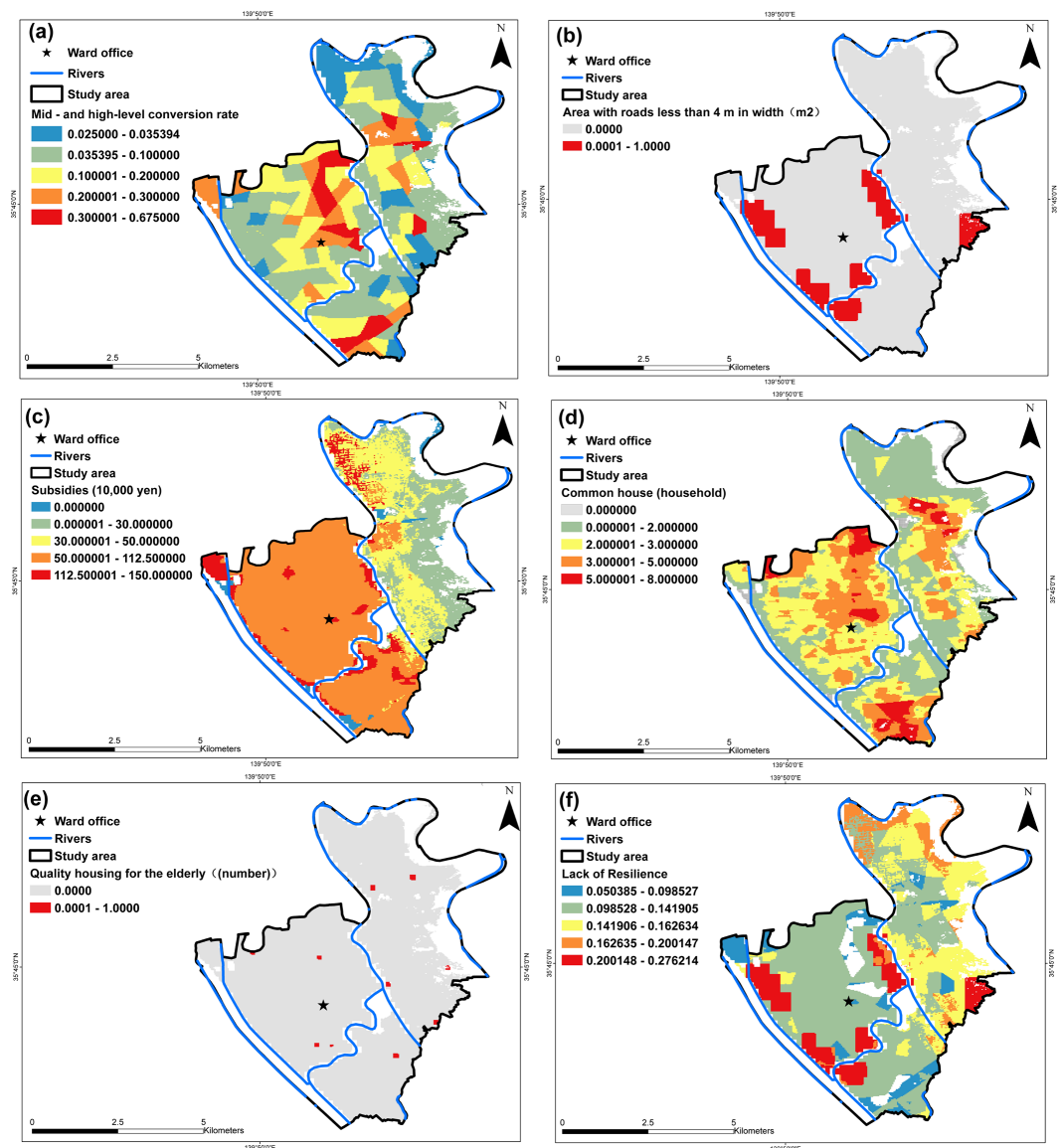


Figure 6. Response ability of residential buildings to floods. (a) Distribution of mid- and high-level conversion rate; (b) distribution of area with roads less than 4 m in width; (c) distribution of subsidy; (d) distribution of common house; (e) distribution of quality houses for older people; (f) distribution of response ability of residential buildings to flood.

Figure 7 illustrates the spatial distribution of flood risk in the study area for residential buildings. This risk assessment integrates four key factors: hazard level, exposure level, vulnerability, and response capacity. The resultant disaster resilience was categorized into five levels: extremely low, low, medium, high, and extremely high. The ‘extremely high’ risk level was predominantly concentrated in the southwest, followed by the northwest. ‘High’ and ‘medium’ risk levels were distributed across western and certain southeastern areas. Conversely, ‘low’ risk levels were prevalent in the eastern region, with pockets in the northwest and southwest. The ‘extremely low’ risk level was primarily located in the north, with a concentration in the east.

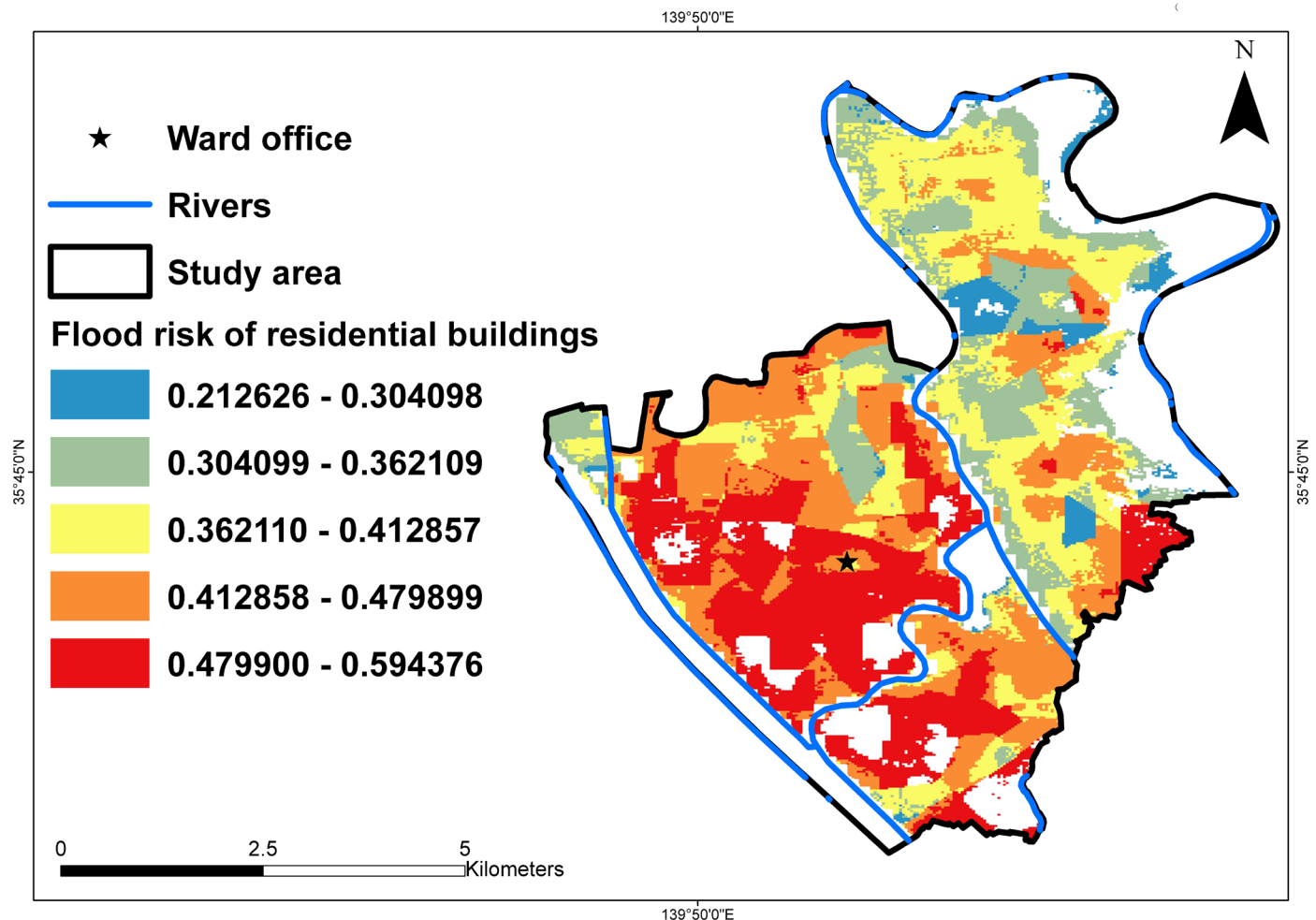


Figure 7. Flood risk of residential buildings.

4. Discussion

Katsushika Ward was selected as the study area due to its unique combination of hydrogeological and socio-demographic characteristics that amplify flood vulnerability. Situated in Tokyo’s lowest-lying region with five major rivers traversing the area, the ward exhibits classic floodplain morphology exacerbated by land subsidence. This geomorphological predisposition intersects with concentrated urbanization patterns—residential land use is dominated by aging wooden structures and narrow road networks. These factors make Katsushika Ward a representative case for studying urban residential flood risks [41].

In the assessment of flood hazards to residential buildings, immersion depth is a more critical factor than immersion duration. Notably, residential buildings in the western region face higher risks than those in the eastern region do. When coupled with prolonged

immersion duration, this amplified the range for residential structures in the southwest. Therefore, prioritized disaster prevention and mitigation efforts are imperative in the southwest region. Additionally, focusing on height and quality improvements in housing can enhance disaster-prevention measures. For instance, the 2013 disaster prevention plan for the study area proposed essential measures, including refuge advice, preparation, and instruction, aimed at mitigating and preventing disasters [59,60]. Furthermore, the introduction of building height restrictions in 2014 within this study area demonstrated another effective approach to enhance disaster prevention capabilities [61].

The analysis of flood exposure for residential buildings highlights the critical importance of factors such as household numbers and homestead rates. A high degree of exposure to floods was notable in the northwest, with localized high exposure in the southeast and southwest. Disaster subsidies and compensation mechanisms differed between owner-occupiers and renters in the flood scenarios. Therefore, it is essential to include the renter population when addressing exposure-reduction strategies.

The vulnerability of residential buildings to floods relies significantly on indicators, such as empty houses, one-person households, and single-family homes. Empty houses were notably concentrated along the western riverbank in the southern region, the southeastern area, and certain sections of the northwest. Inadequate management of vacant houses poses challenges in terms of disinfection and reconstruction in the event of a flood, thereby increasing the vulnerability of residential buildings. Both one-person and single-family homes exhibit limited disaster prevention and reconstruction capabilities. Furthermore, one- and two-story wooden residential buildings face increased flood risk owing to their high hazard exposure, which is attributed to the deepening of immersion depth and prolonged flooding. To mitigate vulnerability, proactive management of vacant property and enhancement of disaster prevention and reconstruction capacity for one-person households, single-family homes, and one- and two-story wooden residential buildings are essential. Government-initiated disaster prevention plans for areas around Yotsugi Station, Horikiri 2-chome, and Horikiri 4-chome were examined to establish secure and resilient residential structures [62,63].

According to the analysis of the ability of residential buildings to respond to flood events, areas with streets less than 4 m in width and mid- and high-level conversion rates are of great significance. These areas are mainly identified in the northwestern and southeastern regions, most of which are coastal areas. Residential buildings close to these areas are located in places with deep immersion depths and long immersion durations. Moreover, because of the narrow roads, rescuing the owners of houses in post-disaster reconstruction can be challenging, with a low response ability. The regions with low mid- and high-level urbanization rates are mostly located in the west and along the river, with a low response ability. Therefore, to improve the response ability, it is necessary to enhance the disaster resistance and mitigation ability of streets and floors along the river.

The assessment prioritizes key indicators, including response ability, vulnerability, degree of exposure, and extent of hazard, based on their significance. Given the immobility of residential buildings, mitigating risks pertaining to the hazard extent and exposure level is challenging. The effective reduction of flood risk relies on enhancing response capabilities and minimizing vulnerabilities. Notably, an increase in common housing amplifies flood protection for economically disadvantaged people. For instance, a previous study analyzed the district government's initiatives, such as low-rent district houses and accommodations for low-income families [46]. Notably, regions with higher immersion depths, particularly in the northeast, have greater subsidies than those in the southeast, where concentrations of common housing are also prevalent. Improving system resilience requires a comprehensive approach that integrates subsidies and disaster management strategies within common

housing frameworks. This is exemplified by the district government's provision of high-quality, affordably-priced public rental housing for older adults [55].

Compared to previous studies, there are two similarities. First, the high-risk nature of the western region aligns with the high-risk areas identified in the official maps as 'north of the Keisei Mainline and along the Nakagawa River.' Second, the uniqueness of the southeastern area—characterized by poor resilience due to low elevation and inadequate drainage infrastructure, low medical facility density, and weak household evacuation capacity—corresponds with the high-risk features of the southeastern region (e.g., Kameari and Shinshuku areas) in the official maps, which are attributed to low-lying terrain and historical flood frequency [60,64,65].

5. Conclusions

This study employed the AHP-CRITIC method integrated with GIS technology to assess flood risk for residential buildings in Katsushika Ward, Tokyo. An indicator system encompassing four critical dimensions (extent of hazard, degree of exposure, vulnerability, and response ability) and 17 localized indicators was developed and applied. The analysis revealed significant spatial heterogeneity in flood risk across the ward. Areas classified as 'extremely high' and 'high' risk were predominantly concentrated in the northwestern and southwestern riverine zones. These high-risk areas are characterized by dense populations, substantial asset concentration, deep immersion depths, prolonged inundation durations, a high prevalence of vulnerable wooden housing structures, and narrow road networks that impede rescue and recovery operations. Key findings indicate that flood risk for residential buildings is primarily driven by vulnerability and response capacity. Consequently, effective mitigation strategies should prioritize reducing vulnerability through proactive management of vacant properties and enhancing disaster prevention and reconstruction capabilities for vulnerable housing types (e.g., single-person households, single-family houses, single/double-story buildings, and wooden structures). Simultaneously, improving response capacity necessitates strengthening flood resilience measures for streets and buildings along riverbanks, such as widening critical access routes and promoting mid-to-high-rise building conversions.

This study's methodology and findings hold significant implications for flood risk management in densely populated, low-lying urban areas globally. The integration of the AHP-CRITIC method with GIS provides a replicable framework for cities facing similar challenges, particularly in coastal or riverine regions vulnerable to climate change-induced flooding. By prioritizing localized vulnerability factors—such as aging infrastructure, narrow road networks, and socioeconomically disadvantaged populations, the approach underscores the need for tailored urban planning policies. For instance, the emphasis on enhancing mid-to-high-rise housing conversions and improving post-disaster subsidies aligns with global agendas for climate-resilient infrastructure, such as the UN Sustainable Development Goals. This study employs 25-m grid data that meet regional-scale analytical requirements, suitable for district-level strategic planning and disaster emergency zoning in small areas. The flood simulation data are based on a 200-year return period assumption, applicable for large-scale flood disaster management. Considering data accessibility and quantitative requirements, the indicator system does not include metrics such as residents' disaster preparedness awareness or emergency plan implementation efficiency. For instance, social resilience factors, including self-evacuation capabilities in the older people population clusters and community mutual-aid network strengths, were not incorporated into the assessment.

Future studies should explore ways to integrate these qualitative or survey-based social resilience indicators into the assessment framework. Additionally, the methodology

focused on static risk assessment. Developing dynamic models that incorporate real-time data (e.g., rainfall forecasts, sensor networks) or simulate post-disaster recovery processes could further enhance practical utility for emergency management and adaptive planning.

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