

Flood Risk Assessment Based on Game Theory Combination Weighting—A Case Study of Wuwei Region (Postprint)

Authors: Su Guangquan

Date: 2022-06-02T00:00:00+00:00

Abstract

Flood disasters are the most frequent natural disasters worldwide. China is one of the regions experiencing the most significant increase in flood risk globally. In response to the actual situation of frequent mountain flood disasters in Wuwei City, Gansu Province, this study employs a flood assessment method based on game theory combination weighting that integrates subjective and objective weights, utilizes GIS technology, and constructs a flood risk assessment index system comprising 7 indicators from three dimensions—hazard factor severity, disaster-forming environment stability, and disaster-bearing body vulnerability—to obtain the spatial distribution of flood risk degrees for each assessment unit. The assessment results demonstrate that the overall flood risk level of Wuwei City is relatively low, which shows good agreement with historical flood event data. Specifically, high-risk flood areas account for only 4.94% of the total area, concentrated at the junction of Liangzhou District and Gulang County and in the southwestern region of Tianzhu Tibetan Autonomous County; the combined area of relatively low-risk and low-risk zones constitutes 43.84% of the total area, concentrated in the eastern desert region of Minqin County. Through comparison between single weighting methods and the game theory combination weighting method, it is shown that the game theory combination weighting method can reduce the subjectivity inherent in single weighting methods, improve the accuracy of flood risk maps, and provide a basis for flood risk management.

Full Text

Preamble

Flood Risk Assessment Based on Game Theory Combination Weighting: A Case Study of the Wuwei Region

Su Guangquan^{1,2}, Lü Haishen^{1,2}, Zhu Yonghua^{1,2}, Chen Tingxing^{1,2},
Hua Jiacheng^{1,2}

¹State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, Jiangsu

²College of Hydrology and Water Resources, Hohai University, Nanjing, Jiangsu

Abstract

Floods are the most frequent natural disasters worldwide, and China has experienced one of the most significant increases in flood risk globally. Given the frequent occurrence of flash floods in Wuwei City, Gansu Province, this study employs a flood risk assessment method that combines subjective and objective weights based on game theory, applied through GIS technology. Seven indicators were selected to construct a flood risk assessment index system from three aspects: hazard of disaster-causing factors, stability of the disaster-forming environment, and vulnerability of disaster-bearing bodies. The spatial distribution of flood risk for each evaluation unit was obtained. The results indicate that the overall flood risk level in Wuwei City is relatively low, which aligns well with historical flood event data. High-risk areas account for only 4.94% of the total area, concentrated at the junction of Liangzhou District and Gulang County, as well as in the southwestern part of Tianzhu Tibetan Autonomous County. The combined area of lower-risk and low-risk zones accounts for 43.84% of the total area, primarily concentrated in the eastern desert region of Minqin County. By comparing single weighting methods with the game theory combination weighting approach, the study demonstrates that the game theory method can reduce the subjectivity of single weighting methods and improve the accuracy of flood risk mapping, providing a basis for flood risk management.

Keywords: flood disaster; risk zoning; analytic hierarchy process; game theory; entropy method; Wuwei Region

1. Study Area and Methods

1.1 Study Area Overview

Wuwei Region is located in central Gansu Province, geographically positioned between 36°29' -39°27' N and 101°49' -104°16' E, covering an area of 32,345 km². It lies at the intersection of the Loess Plateau, Qinghai-Tibet Plateau, and Mongolian-Xinjiang Plateau [Figure 1: see original paper]. The southern region borders the Qilian Mountains, the central area comprises the Hexi Corridor plain, and the north meets the Tengger and Badain Jaran deserts. Elevation ranges from 1,200 to 4,700 m, gradually decreasing from south to north. Annual precipitation varies between 100-600 mm, with the highest rainfall occurring in

July and August, showing a decreasing trend from south to north. The region experiences strong evaporation and dry air. Major rivers include the Yellow River and Shiyang River, with the Shiyang River originating from the eastern Qilian Mountains. Its upper reaches consist of the Xiying, Huangyang, and Xida rivers, while its lower reaches flow into the desert basin of Minqin County, with a watershed area of 3.98×10^4 km².

1.2 Research Methods

Based on disaster risk theory and the natural environment and socio-economic characteristics of Wuwei, this study selected seven indicators from three aspects—hazard of disaster-causing factors, stability of disaster-forming environment, and vulnerability of disaster-bearing bodies—to construct the flood risk assessment index system. The research process involves four main steps: First, build the flood risk assessment index system; second, preprocess the indicator layers using GIS technology, calculate objective weights using the entropy method and subjective weights using the analytic hierarchy process (AHP), and then combine them using game theory; third, construct the Wuwei flood risk assessment model using fuzzy comprehensive evaluation based on the game theory combination weights, and classify flood risk levels into five categories (high, relatively high, medium, relatively low, and low) using the natural breaks method; finally, validate the model against historical flood data and compare it with single weighting methods to verify effectiveness. The research flowchart is shown in [Figure 2: see original paper].

1.3 Flood Risk Assessment Index System

Based on disaster risk theory, this study reveals regional disaster mechanisms through assessment of disaster-causing factor hazards, analysis of disaster-forming environment stability, and evaluation of disaster-bearing body vulnerability [6,7,21]. The following flood risk assessment indicators were selected: historical maximum daily rainfall (R), rainstorm frequency (R), elevation standard deviation (E), normalized difference vegetation index (NDVI), water system distance (D), population density (P), and GDP density (G). The content, sources, and processing methods for each indicator are described below.

1.3.1 Disaster-Causing Factor Indicators Historical Maximum Daily Rainfall (R): Rainstorms are the primary cause of floods in Wuwei, and historical maximum rainfall reflects the potential maximum flood loss. Data were obtained from the $0.5^\circ \times 0.5^\circ$ gridded dataset of the National Meteorological Science Data Center (<http://data.cma.cn/>) for 1961–2015. The inverse distance weighting interpolation method was used to calculate daily rainfall data for the study area.

Rainstorm Frequency (R): Areas with more frequent rainstorms have higher future flood probability. Based on Wuwei's gridded rainfall data,

the frequency of daily rainfall exceeding 30 mm was counted, and Kriging interpolation was applied to generate rainstorm frequency data.

1.3.2 Disaster-Forming Environment Indicators Elevation Standard Deviation (E): Higher elevation standard deviation indicates greater topographic relief, making flash floods more likely. Original 90m resolution DEM data from SRTMDEM 90M (<https://www.gscloud.cn/search>) were used, and neighborhood analysis was applied to calculate elevation standard deviation for the study area.

Normalized Difference Vegetation Index (NDVI): Vegetation directly affects runoff generation and concentration processes, significantly influencing flood timing and magnitude. Data were obtained from the Chinese Academy of Sciences Resource and Environmental Science and Data Center (<https://www.resdc.cn/>).

Water System Distance (D): Areas closer to rivers and lakes are more vulnerable to flood inundation. Water system data were derived from national standard vector map data (<https://www.webmap.cn/main.do?method=index>), and nearest neighbor analysis was used to calculate distances to water systems.

1.3.3 Disaster-Bearing Body Vulnerability Indicators Population Density (P) and GDP Density (G): Floods have social attributes, and losses differ across regions with varying economic and population characteristics. Both population density and GDP density raster data were obtained from the Chinese Academy of Sciences Resource and Environmental Science and Data Center (<https://www.resdc.cn/>).

After establishing the evaluation index system, all indicator layers were preprocessed by resampling to 1 km resolution and standardized using raster calculator. The standardization method is shown in Equation (1).

1.4 Entropy Weight Method

Entropy, originating from thermodynamics, describes the irreversibility of molecular motion. In information theory, entropy reflects the degree of information disorder and can measure information quantity. Indicators carrying more information have greater decision-making significance, resulting in smaller entropy values and greater system disorder [22]. The main steps for calculating indicator weights are:

- 1) **Indicator Data Standardization:** For positive indicators (larger-is-better type):

$$r_{ij} = \frac{a_{ij} - a_j^{\min}}{a_j^{\max} - a_j^{\min}}$$

For negative indicators (smaller-is-better type):

$$r_{ij} = \frac{a_j^{\max} - a_{ij}}{a_j^{\max} - a_j^{\min}}$$

where a_j^{\max} and a_j^{\min} are the maximum and minimum values of indicator j , a_{ij} is the value of indicator j in evaluation unit i , and r_{ij} is the standardized value.

2) **Calculate Indicator Entropy:**

$$H_j = -\frac{1}{\ln m} \sum_{i=1}^m f_{ij} \ln f_{ij}$$

where $f_{ij} = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}}$, m is the number of basic grid units, n is the number of indicators, and H_j is the entropy of indicator j (with $f_{ij} \ln f_{ij} = 0$ when $f_{ij} = 0$).

3) **Calculate Entropy Weight:**

$$w_j = \frac{1 - H_j}{n - \sum_{j=1}^n H_j}$$

1.5 Analytic Hierarchy Process (AHP)

The fundamental principle of AHP involves decomposing various elements of the evaluation system into a hierarchy of goals, criteria, and indicators, conducting pairwise comparisons, calculating element weights, and selecting the optimal scheme based on maximum weight principle. AHP is highly operational and structurally flexible. The basic steps are:

- 1) **Construct Hierarchical Structure:** The research object is stratified into three levels: goal layer, criterion layer, and indicator layer.
- 2) **Construct Judgment Matrix:** Pairwise comparisons of elements at the same level produce a judgment matrix, typically using the 1-9 scale method for importance grading.
- 3) **Hierarchical Single Sorting:** Pairwise comparisons determine the relative importance of elements and calculate weights relative to the upper level.

1.6 Game Theory Combination Weighting

Game theory combination weighting is widely applied in natural disaster risk assessment [23]. In game theory, all schemes are assumed to be rational decisions seeking optimal overall system benefits. The final result is not controlled by a single decision-maker but achieved collectively by all decision-makers [24]. This

can be formulated as a multi-objective optimization problem that seeks consistency or compromise among different weighting methods, minimizing deviation between the final weighting result and each basic method' s weights.

The specific steps are as follows:

- 1) **Assume L methods are used for weighting, with each method producing a weight vector $\omega_k = (\omega_{k1}, \omega_{k2}, \dots, \omega_{kn})^T$. Any linear combination of these L vectors is:

$$\omega = \sum_{k=1}^L \beta_k \omega_k^T$$

where ω is the possible combined weight vector, ω_k^T is the weighting result of method k , and β_k are weighting coefficients with $\beta_k > 0$.

- 2) **To obtain the optimal weight combination, the deviation between the game theory combination weight vector and each method' s weight vector must be minimized. The optimal weight coefficients are determined by:

$$\min \left\| \sum_{k=1}^L \beta_k \omega_k^T - \omega_k \right\|_2$$

- 3) **Expanding this yields a linear equation system. Solving the following system gives the optimal weight coefficients:

$$\begin{pmatrix} \omega_1 \omega_1^T & \omega_1 \omega_2^T & \dots & \omega_1 \omega_L^T \\ \omega_2 \omega_1^T & \omega_2 \omega_2^T & \dots & \omega_2 \omega_L^T \\ \vdots & \vdots & \ddots & \vdots \\ \omega_L \omega_1^T & \omega_L \omega_2^T & \dots & \omega_L \omega_L^T \end{pmatrix} \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_L \end{pmatrix} = \begin{pmatrix} \omega_1 \omega_1^T \\ \omega_2 \omega_2^T \\ \vdots \\ \omega_L \omega_L^T \end{pmatrix}$$

- 4) **After obtaining the optimal weight coefficients from the linear system, normalize them and substitute into the combination formula to obtain the game theory combination weighting result.

2. Results and Analysis

2.1 Multi-Method Comparison Analysis

Game theory combination weighting integrates results from different weighting methods, requiring consistency testing among them. Based on flood risk disaster theory, the evaluation index system was constructed, and expert evaluation was used to build the judgment matrix. All hierarchical indicator weights passed consistency checks. The consistency degree among different weighting methods can be measured by distance functions, where smaller distances indicate higher consistency. The study considers $d(\omega^{(1)}, \omega^{(2)}) \leq 0.4$ as passing the consistency test.

After consistency testing, the entropy method and AHP were combined. The entropy method calculated flood risk indicator entropy values to obtain objective weights, while AHP provided subjective weights. Both methods passed consistency testing, yielding game theory combination weighting coefficients of $\beta_1 = 0.525$ and $\beta_2 = 0.475$.

The entropy weighting results show that population density, GDP density, and rainstorm frequency have greater influence on Wuwei's flood risk, while neglecting environmental factors like elevation standard deviation and water system distance that exacerbate flood hazards. AHP results indicate that elevation standard deviation, historical maximum daily rainfall, and rainstorm frequency are more influential, but lack consideration of vulnerability indicators like population and GDP density. Neither single method comprehensively integrates all three aspects: disaster-causing factor hazards, disaster environment stability, and disaster-bearing body vulnerability. The game theory combination weighting better reflects expert subjective judgment while overcoming limitations of objective weights.

To validate the combination weighting method's effectiveness, fuzzy comprehensive evaluation models were constructed using three methods, with flood risk classified by the natural breaks method. The resulting flood risk spatial distribution maps show significant differences in both risk area proportions and spatial patterns among methods. The entropy method underestimates risk in 56.34% of areas and overestimates in 2.88% compared to the combination method, with only 40.78% agreement. AHP shows 37.86% underestimation and 8.24% overestimation, with 53.90% agreement. The combination method demonstrates higher consistency with historical flood distribution, accurately identifying vulnerable areas without overestimating risk.

2.2 Historical Flood Validation

According to *China Meteorological Disaster Canon*, *China Meteorological Disaster Yearbook*, and related literature [25], historical floods were statistically analyzed and overlaid on flood risk maps generated by entropy method, AHP, and game theory combination weighting. The flood risk evaluation grades were determined, with historical floods classified into five levels based on relevant studies [26]: high risk (floods occurring ≥ 5 times), relatively high risk (3–4 times), medium risk (2 times), relatively low risk (1 time), and low risk (0 times).

Comparison results show that entropy method and AHP produce significantly different flood risk zoning, indicating uncertainty in single-method assessments. Focusing on medium-to-high risk areas (the primary concern in flood assessment), AHP mostly overestimates risk in these regions, with only 26.31% consistency with historical evaluation. The entropy method substantially underestimates risk, particularly failing to identify high-risk areas, with only 21.05% consistency. The combination method performs most accurately, achieving 42.11%

consistency with historical data, though it slightly overestimates in medium-risk areas. For low and relatively low-risk areas, all methods show some overestimation, with the entropy method performing best. Overall, the game theory combination weighting better reflects Wuwei's flood risk distribution patterns, accurately identifying flood-vulnerable areas without overestimation. Therefore, subsequent analysis focuses solely on the combination weighting flood risk map [Figure 3: see original paper].

2.3 Flood Risk Zoning Analysis

Flood risk zoning analysis identifies sub-regional risk levels and sources. Based on [Figure 4: see original paper], Wuwei's overall flood risk decreases from southwest to northeast. High-risk areas are concentrated in the upper reaches of the Shiyang River, Xiyang River, Wuba River, Huangyang River, and Shagou River in southwestern Liangzhou District, as well as the Gansha River and Maozang River in southwestern Tianzhu Tibetan Autonomous County. Liangzhou District's high-risk area accounts for 14.53% of its total area, primarily due to high disaster-bearing body vulnerability. The southwestern part of Liangzhou District lies at the northern foothills of the Qilian Mountains with dense river networks, concentrated rainfall, high population density, and developed economy, where floods would cause severe losses. Tianzhu County's high flood risk stems from disaster-causing factor hazards, as its southwestern region is affected by the Qilian Mountains with frequent rainfall and heavy rainstorms. Low-risk areas are mainly concentrated in the eastern desert region of Minqin County, accounting for 56.28% of the total area. This is because Minqin County is located at the intersection of the Tengger and Badain Jaran deserts, creating a unique desert climate with historically scarce rainfall, strong evaporation, poor water storage capacity, and sparse river networks and population density.

3. Conclusions

Based on the Wuwei flood risk map and comparison with measured historical flood data and flood risk maps from related studies in the region, this research demonstrates accurate flood risk zoning for Wuwei. The main conclusions are:

- 1) The game theory combination weighting method, integrating subjective and objective weights, reduces limitations of single approaches and improves flood risk map accuracy.
- 2) Wuwei City's overall flood risk level is relatively low, showing a decreasing distribution characteristic from southwest to northeast. High-risk areas are concentrated at the junction of Liangzhou District and Gulang County and in southwestern Tianzhu Tibetan Autonomous County, while low-risk areas are mainly distributed in the desert region of Minqin County. High-risk areas account for only 4.94% of the total area, while relatively low-risk and low-risk areas account for 43.84%.

- 3) The main sources of flood risk vary among counties in Wuwei. Disaster-causing factor hazards show a belt-like distribution decreasing from southwest to northeast, with high-hazard areas mainly in the Qilian Mountains region of Tianzhu County and low-hazard areas concentrated in the lower reaches of the Shiyang River in the northeast. Disaster environment stability is relatively uniform, except for higher stability in the Qilian Mountains region, with similar stability in the central Hexi Plain and eastern desert areas. Disaster-bearing body vulnerability shows significant regional differences, with vulnerability at the junction of Liangzhou District and Gulang County being much higher than in other regions.

References

- [1] Hirabayashi Y, Mahendran R, Koirala S, et al. Global flood risk under climate change[J]. *Nature Climate Change*, 2013, 3(9): 816-821.
- [2] Xu H S, Ma C, Lian J J, et al. Urban flooding risk assessment based on an integrated k-means cluster algorithm and improved entropy weight method in the region of Haikou, China[J]. *Journal of Hydrology*, 2018, 563: 975-986.
- [3] Chen X L, Zhang H, Chen W J, et al. Urbanization and climate change impacts on future flood risk in the Pearl River Delta under shared socioeconomic pathways[J]. *Science of the Total Environment*, 2021, 762: 1-14.
- [4] Quirós E, Gagnon A S. Validation of flood risk maps using open source optical and radar satellite imagery[J]. *Transactions in GIS*, 2020, 24(5): 1208-1226.
- [5] Ye Aimin, Liu Shuguang, Han Chao, et al. Application of MIKE FLOOD coupling model in flood risk mapping at Jiaying area of Zhejiang Province[J]. *China Flood & Drought Management*, 2016, 26(2): 56-60.
- [6] Sun Yuhang, Cheng Shupeng, Zhang Qi, et al. Research on flood risk assessment of floodplains from Huayankou to Aishan section in the lower Yellow River[J]. *Acta Scientiarum Naturalium Universitatis Pekinensis*, 2021, 57(3): 575-586.
- [7] Huang Chongfu, Guo Jun, Ai Fuli, et al. Basic paradigm of risk analysis in flood disaster and its application[J]. *Journal of Natural Disasters*, 2013, 22(4): 11-23.
- [8] Wang Zhaoli, Lai Chengguang, Chen Xiaohong. Spatially fuzzy comprehensive assessment model for flood hazard risk based on entropy weight[J]. *Journal of Hydroelectric Engineering*, 2012, 31(5): 35-40.
- [9] Li Chunhua, Ye Chun, Zhao Xiyang, et al. The ecosystem health assessment of the littoral zone of Lake Taihu[J]. *Acta Ecologica Sinica*, 2012, 32(12): 3806-3815.
- [10] Chen Jialiang. Research on evaluation method of combination weighting based on game theory[J]. *Journal of Fujian Computer*, 2003(9): 15-16.

- [11] Pei Huijuan, Chen Jin, Li Wen, et al. Spatiotemporal pattern and risk assessment of storm flood in Gansu Province[J]. *Journal of Natural Disasters*, 2017, 26(3): 167-175.
- [12] Xu Kaili, Lyu Haishen, Liu Minwen, et al. Numerical simulation of the ice jam stage in the Sanhuhekou bend reach of the Yellow River[J]. *Arid Zone Research*, 2021, 38(6): 1556-1562.
- [13] Shi Peijun. Theory on disaster science and disaster dynamics[J]. *Journal of Natural Disasters*, 2002, 11(3): 1-9.
- [14] Zhang Hongping. Study on the Flood Risk Management and Technology of the Small Mountain Watershed[D]. Beijing: China Institute of Water Resources & Hydropower Research(IWHR), 2013.
- [15] Meng Xianmeng, Hu Heping. Application of set pair analysis model based on entropy weight to comprehensive evaluation of water quality[J]. *Journal of Hydraulic Engineering*, 2009, 40(3): 257-262.
- [16] Lu Yao, Xu Linrong, Chen Shuyang, et al. Combined weight method based on game theory for debris flow hazard risk assessment[J]. *Journal of Catastrophology*, 2014, 29(1): 194-200.
- [17] Gan Rong, Xuan Hao, Liu Guodong, et al. Application of weighted matter element extension based game theory in groundwater quality evaluation[J]. *Water Resources and Power*, 2015, 33(1): 39-42.
- [18] Chen Tingxing, Lyu Haishen, Zhu Yonghua. Analysis of flood characteristics in Xiying River Basin based on GEV distribution[J]. *Arid Zone Research*, 2021, 38(6): 1563-1569.
- [19] Zhang Junlan, Luo Ji, Wang Rongmei. Combined analysis of the spatiotemporal variations in snowmelt (ice) flood frequency in Xinjiang over 20 years and atmospheric circulation patterns[J]. *Arid Zone Research*, 2021, 38(2): 339-350.
- [20] Zhou Gang, Cui Manyi, Li Zhe, et al. Dynamic evaluation of the risk of the spring snowmelt flood in Xinjiang[J]. *Arid Zone Research*, 2021, 38(4): 950-960.
- [21] Liu Y, Lu X Y, Yao Y Z, et al. Mapping the risk zoning of storm flood disaster based on heterogeneous data and a machine learning algorithm in Xinjiang, China[J]. *Journal of Flood Risk Management*, 2020, 14(1): 1-14.
- [22] Lian J J, Xu H S, Xu K, et al. Optimal management of the flooding risk caused by the joint occurrence of extreme rainfall and high tide level in a coastal city[J]. *Natural Hazards*, 2017, 89(1): 183-207.
- [23] Straatsma M W, Kleinhans M G. Flood hazard reduction from automatically applied landscaping measures in river scape, a python package coupled to a two dimensional flow model[J]. *Environmental Modelling and Software*, 2018, 101: 102-116.

[24] Wang Rongzhe, Li Lingping, Li Wenli. Risk division of flood disaster in Wuwei based on GIS[J]. Journal of Arid Meteorology, 2013, 31(3): 602-608.

[25] Huang Chongfu, Guo Jun, Ai Fuli, et al. Basic paradigm of risk analysis in flood disaster and its application[J]. Journal of Natural Disasters, 2013, 22(4): 11-23.

[26] Shi Peijun. Theory on disaster science and disaster dynamics[J]. Journal of Natural Disasters, 2002, 11(3): 1-9.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.