

Article

# Spatial Differentiation and Quantitative Assessment of Disaster Risk for Socialist Built Heritage Driven by Meteorological–Environmental Factors in Henan, China

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## Abstract

In response to the escalating challenges of global climate change and extreme meteorological events, this study addresses the critical issue of low disaster resistance in socialist-built heritage (SBH, i.e., built cultural heritage constructed during China's socialist construction stage from 1949 to 1978). Focusing on Henan Province, China, with meteorological observation datasets spanning 1990–2023 and 1362 SBH sites constructed from 1949 to 1978, we innovatively construct a four-dimensional risk assessment model integrating Meteorological–Environmental Hazard (H), Exposure (E), Vulnerability (V), and Ecological Resilience (R). By synthesizing Spearman correlation analysis, Variance Inflation Factor (VIF) diagnostics, and piecewise regression, this research elucidates the spatial differentiation and driving mechanisms of meteorology-induced compound disaster risks. Key findings identify Zhengzhou and Kaifeng as core high-risk zones and precisely quantify a critical hazard threshold of 0.4 with a 95% breakpoint confidence interval [0.372, 0.428], passing the Chow test  $p < 0.001$  and validated via historical heritage damage records ( $R^2 = 0.78$ ). Variable-importance analysis proves that extreme precipitation (32.7%) and annual strong-wind days (28.1%) are the dominant meteorological–environmental drivers, alongside the significant buffering effect of ecological resilience. Ultimately, this study refines the disaster risk assessment framework for SBH, providing robust theoretical support and a decision-making basis for adaptive conservation strategies in similar regions. The average disaster risk of SBH in Henan is  $0.421 \pm 0.153$ ; for each 0.1 growth of H-E-V coupling term above the threshold of 0.4, disaster risk rises by 37.2%.

**Keywords:** socialist-built heritage; meteorological–environmental; disaster risk; spatial differentiation



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## 1. Introduction

In the context of global climate change, meteorological–environmental (ME) factors have evolved from exerting slow, gradual influences to becoming a core driving force behind sudden, high-intensity, and chain-reaction destruction. The IPCC Sixth Assessment Report underscores that meteorological variations, such as rainwater infiltration, wind erosion, and wet–dry cycles, accelerate material degradation, structural attenuation, and foundation instability in cultural heritage [1].

Against the long-term background of global climate warming, local human socio-economic activities continuously amplify meteorological disaster risks to SBH. Large-scale urban expansion, mineral exploitation in mountainous areas, river channel reconstruction,

and farmland transformation alter regional surface runoff, vegetation coverage, and heat balance, aggravating rainstorm floods, soil erosion, and urban heat island effects. Such human–land coupling pressure superimposes climate change trends, forming compound destructive forces that accelerate the weathering, structural damage, and disappearance of socialist architectural heritage. This creates an urgent demand for targeted quantitative evaluation of meteorological disaster risks.

This threat is particularly acute for SBH, which denotes built cultural heritage constructed during China’s socialist construction stage (1949–1978), including industrial, public, and residential architecture of outstanding historical, artistic, and scientific value. Predominantly composed of brick–concrete and brick–wood [2,3]. These structures are characterized by high meteorological sensitivity and low risk resistance. Consequently, significant portions of this heritage face an escalating crisis of deterioration and potential disappearance under increasingly complex meteorological conditions. Western nations began focusing on the impacts of climatic changes on cultural heritage in the late 20th century, and UNESCO has repeatedly called for integrating climate risks into World Heritage monitoring systems [4,5]. Existing international studies mostly establish climate vulnerability frameworks for European stone historic architecture but lack targeted evaluation systems for China’s brick–concrete/brick–wood SBH. Traditional disaster risk models adopt static H-E-V multiplicative calculation without incorporating system resilience buffer dimension and rarely quantify nonlinear threshold effect of meteorological hazard factors. While Italian scholars have constructed climate vulnerability assessment frameworks for architectural heritage and British teams have developed meteorological response models, such research has largely concentrated on European stone architecture and historic districts, with scant attention paid to SBH [5].

Domestic research on cultural heritage started relatively late; early studies prioritized restoration techniques and stylistic conservation in China [6,7]. Since the beginning of the 21st century, attention has gradually shifted to meteorological impacts, exploring the effects of urban heat islands on the thermal performance of historic buildings. However, these studies often focus on single-hazard scenarios like earthquakes or fires or merely analyze material and structural factors, neglecting the holistic and dynamic nature of regional ME and surface–process interactions [8,9]. Furthermore, there is a notable scarcity of research specifically addressing SBH. The volatility of the ME creates strong nonlinear correlations with heritage disaster risk and regional environmental resilience [10,11], posing a significant challenge for precise quantification in current research.

Henan serves as an ideal case study to address these gaps. Located in the transitional climatic zone between northern and southern China [12], it features a warm temperate continental monsoon climate with significant spatiotemporal variations and frequent extreme disasters [13]. As a key region for the “First Five-Year Plan” and the “Third Front” construction, Henan retains a substantial amount of SBH [14]. The high degree of spatial overlap between heritage distribution and meteorological hazard zones renders the ME factors the primary factor threatening the safety of SBH. Complex west-high-east-low topography creates obvious spatial heterogeneity of rainstorms, gales, and temperature–humidity alternation; massive industrial, hydraulic, and public architectural heritage distributed in alluvial plain piedmont areas highly overlaps with meteorological disaster high-incidence zones, making Henan a typical research area for revealing meteorology-driven SBH disaster risk differentiation. Using SBH in Henan as a case study, this research constructs a four-dimensional disaster risk assessment system based on the ME factors to quantitatively evaluate the spatial differentiation of disaster risk [15,16]. This study not only reveals the driving mechanisms of meteorological factors on heritage disaster risk but also refines

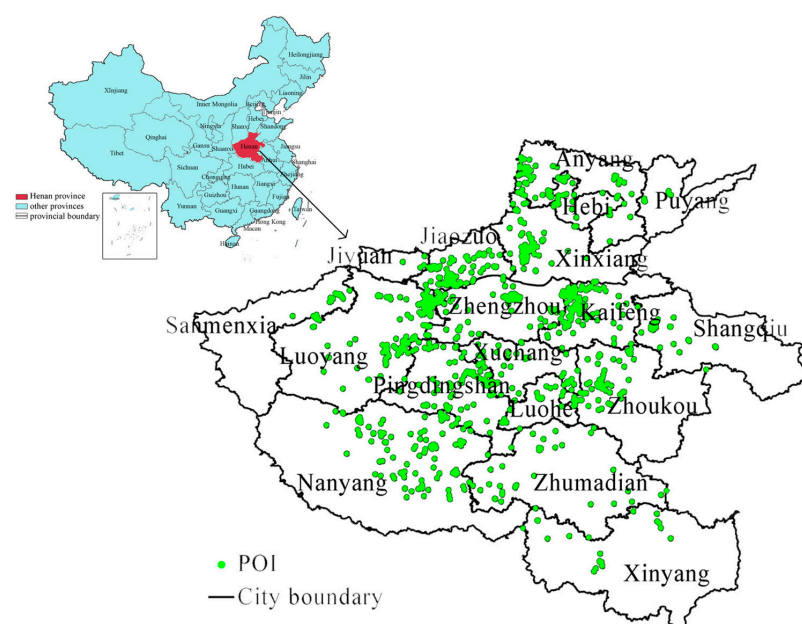
the theoretical framework and technical pathways for meteorological risk assessment, providing references for heritage conservation in similar regions across China [17].

## 2. Study Area and Data Sources

### 2.1. Overview of the Study Area

Henan Province, located in central China, is characterized by complex topography that descends from west to east, transitioning sequentially from mountains and hills to plains. The region experiences distinct seasons and high climatic variability. Influenced by the combined effects of topography and monsoons, it is prone to frequent extreme meteorological events, such as rainstorms, heatwaves, and gales [18]. These events are unevenly distributed spatially, resulting in significant meteorological heterogeneity. As a major demographic and economic hub, Henan retains a substantial inventory of SBH constructed between 1949 and 1978. This heritage encompasses diverse typologies, including industrial, transportation, hydraulic engineering, and public buildings. The disaster risk heterogeneity of this heritage is exacerbated by a combination of regional natural conditions, intense human activity, and varying levels of conservation. Specific challenges, such as aging infrastructure, pressure for the demolition and renovation of industrial heritage, and the prevalence of geological hazards and flood threats [19], further compound these risks. Consequently, Henan serves as a representative region for investigating disaster risks in heritage driven by ME factors.

Between 1949 and 1978, driven by national development strategies and regional demands, Henan witnessed the construction of extensive infrastructure across industrial, transportation, and hydraulic engineering sectors. Zhengzhou, Luoyang, and Nanyang, serving as core developmental hubs, hosted a series of industrial projects with dual military and civilian attributes, alongside the development of railways, highways, and various hydraulic engineering projects. Additionally, to meet the daily production, living, and cultural needs of the populace, public buildings such as cinemas, office blocks, and cultural centers were erected throughout the region [20]. Based on the prevailing academic definition of SBH and tailored to the regional characteristics of Henan, a systematic process of compilation, verification, and screening was conducted. Ultimately, 1362 SBH sites were identified for this study (Figure 1).



**Figure 1.** Distribution map of SBH in Henan Province, China.

## 2.2. Data Sources

The research data encompass SBH, meteorological records, environmental variables, and socioeconomic statistics. To ensure accuracy, completeness, and consistency, all datasets underwent rigorous preprocessing:

- (1) SBH data: compiled from multiple authoritative sources, including the List of Cultural Relic Protection Units in Henan Province, the List of China's Industrial Heritage, the Henan Provincial Chronicles, and municipal-level heritage inventories. Archival sources were supplemented by field verification to identify heritage sites constructed from 1949 to 1978. Key attributes, including construction dates, building materials, and preservation status, were recorded. All spatial data were unified to the WGS84 coordinate system during preprocessing.
- (2) Meteorological data: derived from 127 evenly distributed national ground meteorological stations in Henan Province, with continuous daily observation records from 1990 to 2023. Missing daily meteorological values were gap-filled by linear interpolation using multi-year averages from adjacent surrounding stations. Kriging spatial interpolation was adopted to convert discrete station data into a continuous raster surface. ERA5 reanalysis dataset and Fengyun meteorological satellite remote sensing data were fused by monthly temporal matching; unified spatial resolution resampling to 30 m WGS84 UTM projection via bilinear interpolation realized multi-source meteorological data consistency. Key parameters include temperature, humidity, wind speed, pressure, cloud cover, and surface radiation.
- (3) Topographic data: ASTER GDEM V003 (30 m resolution). Elevation, slope, and aspect were extracted within ArcGIS 10.8.
- (4) Vegetation-coverage data: MODIS NDVI product (250 m resolution), projected consistently with meteorological raster datasets.
- (5) Socioeconomic data: obtained from the Henan Provincial Bureau of Statistics and municipal statistical yearbooks.

## 3. Typology and Disaster Risk Identification of SBH

### 3.1. Typology of SBH in Henan

#### 3.1.1. Classification of SBH in Henan

To implement scientific classification for SBH, this study utilized standardized multi-dimensional attribute indicators (construction year, building material, geographic elevation, functional attribute, protection grade) for quantitative grouping.

Technical flow: hierarchical clustering for preliminary feature grouping of indicators, followed by *K*-means clustering for formal partitioning [21]; the Elbow Method combined with Silhouette coefficient verification to confirm optimal cluster number  $K = 8$  (Silhouette coefficient = 0.71), verifying classification validity. Integrating the functional attributes of the SBH with existing classification standards, the 1362 SBH sites were divided into eight major types:

Roads and bridges: comprising railways, highways, bridges, and associated facilities (122 sites).

Industrial: including industrial workshops, mines, and energy facilities (283 sites).

Public administration: encompassing former People's Commune sites, office buildings, banks, post and telecommunications offices, and public security organs (127 sites).

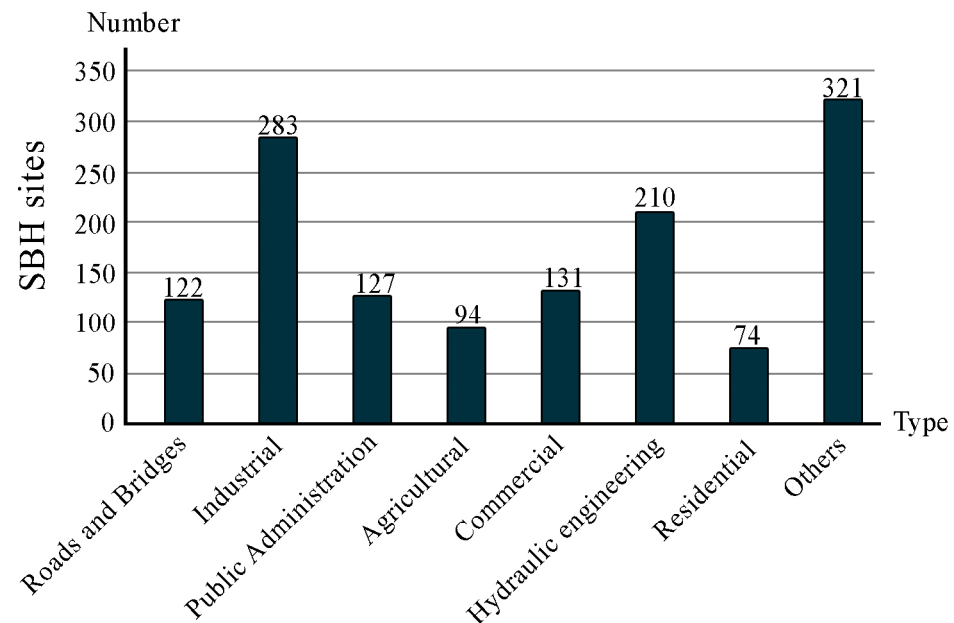
Agricultural: consisting of grain depots, irrigation stations, state-owned farms, forestry centers, and related agricultural research facilities (94 sites).

Commercial: including department stores, supply and marketing cooperatives, hotels, and guesthouses (131 sites).

Hydraulic engineering: comprising reservoirs, sluices, main canals, aqueducts, and Siqing Wells (210 sites).

Residential: including staff quarters, employee dormitories, educated youth settlements, and traditional dwellings (74 sites).

Others: encompassing hospitals, schools, cultural palaces, art centers, clubs, auditoriums, and martyrs' cemeteries (321 sites) (Figure 2).



**Figure 2.** The number of various types of SBH in Henan Province.

### 3.1.2. Temporal Classification of SBH in Henan

The construction history of SBH is intrinsically coupled with the historical stages of China's socialist development. To compare disaster-risk characteristics across different periods, the construction timeline is divided into four phases according to major national historical boundaries:

Stage I (1949–1952): The National Economic Recovery Period.

Stage II (1953–1957): The First Five-Year Plan Period.

Stage III (1958–1965): The Period of Socialist Construction Exploration and Adjustment.

Stage IV (1966–1978): The Cultural Revolution and Third Front Construction Period.

## 3.2. Identification of ME and Disaster Risk for SBH in Henan

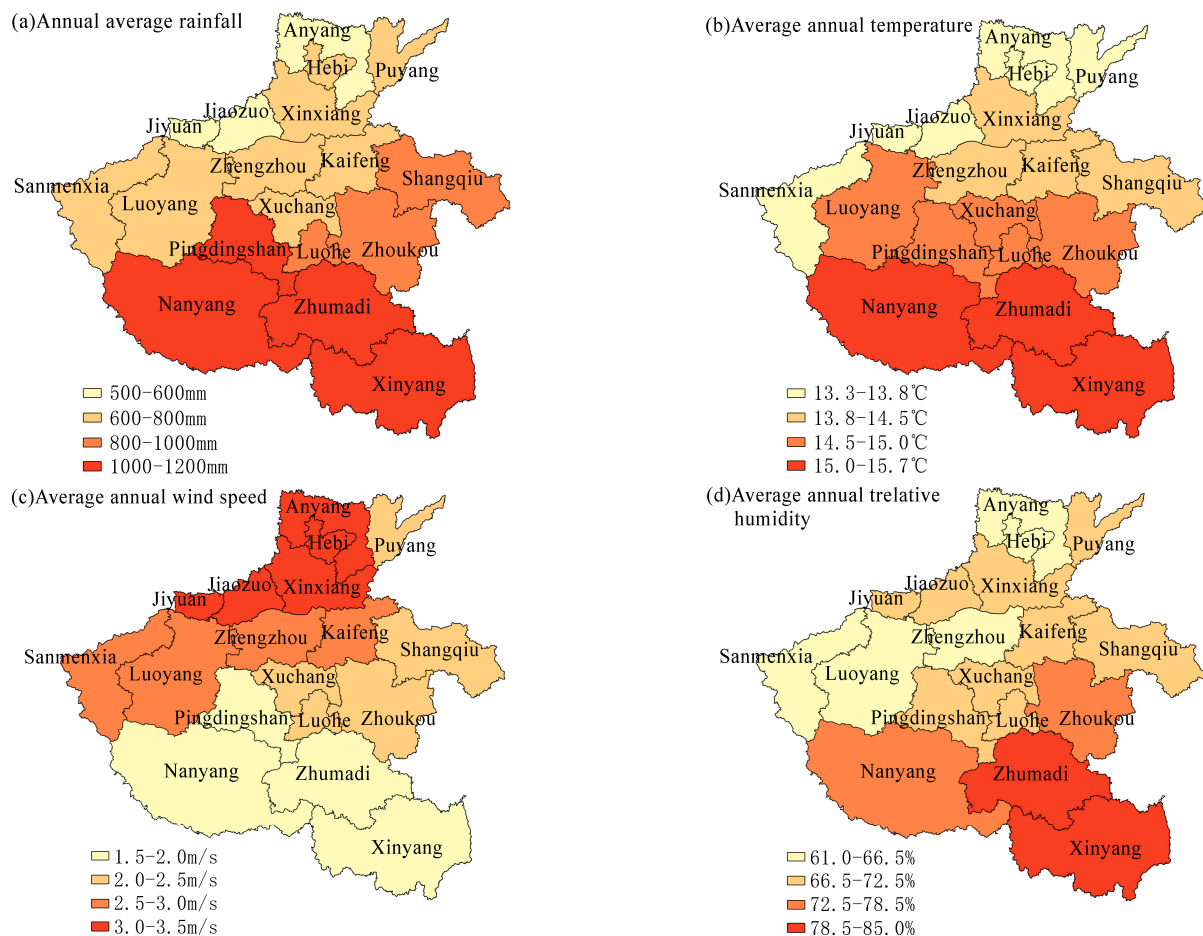
### 3.2.1. Characteristics of the ME Factors in Henan

Henan has complex climatic conditions with substantial annual precipitation, showing a spatial gradient decreasing from south to north and from west to east. The region experiences an average of 3.2 extreme precipitation events annually, showing significant seasonal clustering. High-intensity rainfall in southern and western Henan produces high susceptibility to floods and geological hazards.

The province exhibits a “warm-south, cold-north” thermal pattern; the annual mean temperature is 14.3 °C with an annual temperature range of 28.5 °C. While mountainous areas in western and northern Henan undergo drastic temperature fluctuations, southern Henan remains relatively stable (Figure 3a). The province averages 15.6 days of high temperatures annually. These drastic thermal variations and extreme heat significantly accelerate the weathering and physical deterioration of heritage materials [22].

In terms of wind conditions, the annual-mean wind speed is 2.1 m/s, with the highest speeds recorded in the Taihang Mountain area of northern Henan and the lowest in the south (Figure 3b). The province experiences an average of 23.4 days of strong winds ( $\geq 8$  m/s) annually, reaching up to 28 days in the north [23]. Wind erosion induced by strong winds seriously threatens the structural integrity of heritage buildings (Figure 3c).

Influenced by the southeast monsoon, average relative humidity rises sharply in summer, while winter remains dry with lower humidity levels. This high-humidity environment, combined with frequent wet–dry cycles, exacerbates the decay, mold, and insect infestation of brick–wood structures and the corrosion of metal components, while also causing the pulverization and spalling of brick, stone, and concrete surfaces (Figure 3d).



**Figure 3.** Comparative spatial distribution map of ME factors in Henan.

### 3.2.2. Disaster Risk Identification for SBH in Henan

Henan experiences heavy rainfall and strong winds in summer, contrasted by dry and rainless conditions in winter and spring. Influenced by topography and atmospheric circulation, the region faces multiple threats to its SBH, including floods, wind erosion, drastic temperature and humidity fluctuations, and geological hazards.

#### (1) Flood Hazards

These primarily affect the eastern and southern regions of Henan, impacting hydraulic engineering buildings, open-air industrial heritage, and monumental architecture. Due to the flat terrain and poor drainage, coupled with frequent extreme precipitation, these areas suffer from wall immersion, foundation settlement, material mold, and structural damage, which severely compromise the integrity of the SBH.

## (2) Wind Erosion Hazards

These are mainly distributed across the mountainous areas of northern and western Henan, affecting open-air stone heritage and light industrial structures. Sand and dust carried by strong winds erode heritage surfaces, leading to the weathering and abrasion of stone structures and the loosening and damage of wooden components, thereby reducing the stability of the SBH.

## (3) Temperature and Humidity Fluctuations

These variations cause structural cracking, deformation, and wall spalling in wooden and brick-concrete heritage, significantly shortening their service life.

## (4) Geological Hazards

These are concentrated in the mountainous regions of western Henan and the Taihang Mountains in the north. Precipitation triggers landslides and debris flows, causing direct physical destruction to the SBH sites.

# 4. Meteorological Disaster and SBH Disaster Risk Assessment Model

## 4.1. Theoretical Framework for ME and Disaster Risk Assessment

The core of disaster risk assessment lies in systematically analyzing hazard-occurrence probability and potential impacts on exposed elements. The United Nations Office for Disaster Risk Reduction proposes the classic risk-assessment model:  $\text{Risk} = f(H, E, V)$ . This model assumes disaster risk is jointly determined by H, E, and V. However, this static framework only supports passive-response analysis and ignores the resilience and adaptive capacity of exposed elements.

SBH possesses the dual attributes of irreplaceable cultural value and physical fragility. Consequently, disaster losses depend not only on the intensity of meteorological hazards but also on the resilience levels of the heritage entity, the surrounding environment, and the management system [24]. Therefore, this study introduces R (covering natural-ecological resilience and human-social resilience) as a risk-moderating factor and constructs a four-dimensional disaster risk assessment framework comprising H-E-V-R, targeting meteorology-induced compound disaster risk of SBH:

H: Core meteorological hazard and terrain auxiliary amplification factors;

E: Reflects exposure scale and asset loss potential of heritage sites;

V: Denotes physical structural vulnerability of heritage buildings;

R: Covers vegetation buffer and regional emergency management capacity.

Clarifying the connotations and correlations of elements within each dimension, this framework achieves a systematic and comprehensive assessment of disaster risks for SBH.

## 4.2. Calculation Methods

### 4.2.1. Data Preprocessing and Variable Selection

Given complex nonlinear relationships between meteorological and environmental variables, variable screening is conducted to avoid spurious regression using Spearman correlation analysis and *VIF* multicollinearity diagnostics.

#### (1) Spearman Correlation Analysis

Spearman correlation analysis is used to test monotonic relationships between indicators and risk values and filter low-correlation variables ( $\rho < 0.5$ ).

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2 - 1)} \quad (1)$$

$d_i$ : rank difference for paired variables;  $n$ : the sample size.

(2) *VIF*

*VIF* is used to detect multicollinearity. The standard  $VIF > 5$  indicates severe multicollinearity.

$$VIF_j = \frac{1}{1 - R_j^2} \quad (2)$$

$R_j^2$ : coefficient of determination regressing indicator  $j$  on all remaining predictors.

## 4.2.2. Multi-Dimensional Coupled Risk Model

Following the disaster-risk physical mechanism that risk represents net effect of hazard overcoming environmental resistance, this paper introduces resilience  $R$  as a moderating factor to build the H-E-V-R multiplicative-coupling risk model:

$$Risk_i = \gamma * \frac{H_i^\alpha \cdot E_i^\beta \cdot V_i^\delta}{R_i^\theta} + \epsilon_i \quad (3)$$

$i$ : the evaluation unit;  $H$ ,  $E$ ,  $V$ , and  $R$  are normalized indices for hazard, exposure, vulnerability, and resilience. We set  $\alpha = \beta = \delta = \theta = 1$  for equal-weight multiplicative coupling;  $\gamma = 0.87$  (calibrated by historical heritage-damage samples);  $\epsilon_i$ : residual.

Key preprocessing rules:

Min-max normalization for all indices;  $H$ ,  $E$ , and  $V$  are positive hazard indicators;  $R$  is transformed via reciprocal buffer-effect representation.

Add constant 0.001 to standardized  $R$  to avoid division-by-zero error.

Spatial evaluation unit: prefecture-level city; individual SBH site as inner statistical sample.

## 4.2.3. Measurement of Spatial Heterogeneity

The CV and Moran's  $I$  are adopted to quantify risk dispersion and spatial clustering characteristics.

$$CV = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2}}{\bar{x}} * 100\% \quad (4)$$

Note: A higher CV means a more uneven spatial distribution of risk.

## 5. Selection of Significant Influencing Factors for Meteorological Disaster Risk

Based on the "Pressure-State-Response" (PSR) model, a four-dimensional indicator system incorporating ME factors is constructed [25]. Meteorological variables are mainly distributed within dimensions  $H$ ,  $E$ , and  $R$  to characterize energy input for disaster risk (Table 1).

Equations (1) and (2) were applied for variable screening to mitigate multicollinearity among independent variables [26]. Two indicators (Annual Frequency of Fires, Heritage Value Level) were excluded due to  $VIF > 5$ . Moran's  $I$  spatial autocorrelation test further eliminated Regional Population Density and Social Participation for insignificant spatial autocorrelation ( $p > 0.05$ ). Ultimately, 10 indicators were retained for model calculation (Table 2).

**Table 1.** Disaster risk assessment indicator system and physical significance.

| Dimension | Indicator                       | Physical/Meteorological Significance                                      | Data Processing                                                                                                                                                                                                 |
|-----------|---------------------------------|---------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| H         | Extreme Precipitation Intensity | Driving force of hydraulic scouring and seepage pressure.                 | Calculated based on long-term daily precipitation observation data in the study area, using statistical analysis to determine the precipitation intensity corresponding to the 95th percentile.                 |
|           | Flood Inundation Extent         | Hazard range of extreme hydrological events.                              | Simulated using hydrological and hydraulic models combined with historical flood level data, measured flood data, and basin topographic data to determine inundation boundaries for different return periods.   |
|           | Annual Frequency of Fires       | Annual cumulative characterization of regional fire risk                  | Derived from fire statistics of the regional fire department, taking the average annual number of occurrences.                                                                                                  |
|           | Annual Days of Strong Winds     | Dynamic action of wind load on building envelopes.                        | Based on long-term observation data from regional meteorological stations, counting the number of days per year with wind speeds $\geq 17.2$ m/s (Force 8 gale).                                                |
|           | Elevation                       | Vertical differentiation impact of topography on meteorological elements. | Extracted using GIS spatial extraction tools based on 30 m resolution DEM data.                                                                                                                                 |
|           | Slope                           | Gravitational potential energy and surface runoff velocity.               | Obtained for each evaluation unit using GIS slope calculation tools, expressed as $\tan(\beta)$ .                                                                                                               |
|           | Soil Erosion Modulus            | Comprehensive characterization of hydraulic and aeolian erosion.          | Calculated using the RUSLE model, incorporating five factors: rainfall erosivity, soil erodibility, slope length and steepness, vegetation cover and management, and support practices.                         |
| E         | Distance to Active Faults       | Potential degree of regional impact by seismic disasters.                 | Calculated using GIS spatial analysis tools based on the active fault distribution map and the vector boundary of the study area.                                                                               |
|           | Regional Population Density     | Density of population exposure to disasters in the region.                | Derived from annual census data or statistical yearbooks.                                                                                                                                                       |
| V         | Construction Era                | Time function of material aging and resistance degradation.               | Calculated using the formula $e^{-(2023-Y)}$ , where Y is the construction year of the building. Data on construction years were collected and substituted into the formula to calculate the aging coefficient. |
|           | Structural Type                 | Response differences of structural systems to dynamic loads.              | Assigned values based on the strength of disaster resistance: steel structure (5); frame structure (4); brick–concrete structure (3); brick–wood structure (2); earth structure (1).                            |
|           | Heritage Value Level            | Preciousness and irreplaceability of heritage buildings and monuments.    | Assigned values based on heritage protection standards: national level (5); provincial level (4); municipal level (3); county level (2); general heritage (1).                                                  |

Table 1. Cont.

| Dimension | Indicator                     | Physical/Meteorological Significance                                                                   | Data Processing                                                                                                                                                                                                           |
|-----------|-------------------------------|--------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| R         | Vegetation Coverage           | Reduction effect of vegetation canopy on rainfall kinetic energy.                                      | Calculated using NDVI values derived from remote sensing imagery (e.g., MODIS, Landsat).                                                                                                                                  |
|           | Emergency Response Capability | Adjustment speed of the system to external disturbances.                                               | An evaluation indicator system was constructed (including number of rescue teams, emergency material reserves, traffic accessibility, medical support capability, etc.), and the mean value was taken as the final score. |
|           | Social Participation          | Degree of public participation in disaster prevention, emergency response, and post-disaster recovery. | Based on questionnaire surveys and statistical analysis, combined with community records on disaster prevention and control participation.                                                                                |

Table 2. Screen of significant explanatory factors.

| Dimension | Indicator                       | VIF  | Moran's I | p     | Z     | Remarks  |
|-----------|---------------------------------|------|-----------|-------|-------|----------|
| H         | Extreme Precipitation Intensity | 2.34 | 0.245 **  | 0.000 | 5.87  | Retained |
|           | Flood Inundation Area           | 3.12 | 0.189 **  | 0.003 | 6.95  | Retained |
|           | Annual Frequency of Fires       | 5.14 | 0.156 *   | 0.008 | 8.41  | Excluded |
|           | Annual Days of Strong Winds     | 3.78 | 0.087 *   | 0.36  | 4.42  | Retained |
|           | Elevation                       | 3.45 | 0.278 *** | 0.000 | 5.98  | Retained |
|           | Slope                           | 2.89 | 0.234 **  | 0.002 | 5.45  | Retained |
|           | Soil Erosion Modulus            | 9.12 | 0.123 *   | 0.034 | 7.98  | Retained |
| E         | Distance to Active Faults       | 2.15 | 0.203 **  | 0.005 | 4.78  | Excluded |
|           | Regional Population Density     | 4.12 | 0.312 *** | 0.076 | 4.67  | Excluded |
| V         | Construction Era                | 2.78 | 0.189 **  | 0.000 | 7.67  | Retained |
|           | Structural Type                 | 3.67 | 0.156 *** | 0.002 | 8.34  | Retained |
|           | Heritage Value Level            | 6.31 | 0.267 *** | 0.000 | 12.78 | Excluded |
| R         | Vegetation Coverage             | 3.34 | 0.198 *** | 0.000 | 7.56  | Retained |
|           | Emergency Response Capability   | 3.56 | 0.234 *** | 0.000 | 5.34  | Retained |
|           | Social Participation            | 2.67 | 0.167 **  | 0.064 | 9.45  | Excluded |

Note: *p* denotes the significance of the spatial autocorrelation test; significance thresholds are set at  $p < 0.05$ . Symbols \*, \*\*, and \*\*\* denote statistical significance at the 90%, 95%, and 99% confidence levels, respectively. Distance to Active Faults was excluded because its Moran's I test returned  $p > 0.05$ , and the indicator shows no significant spatial agglomeration matching SBH-risk patterns and delivers weak spatial explanatory power.

## 6. Results and Analysis

### 6.1. Spatial Distribution of SBH

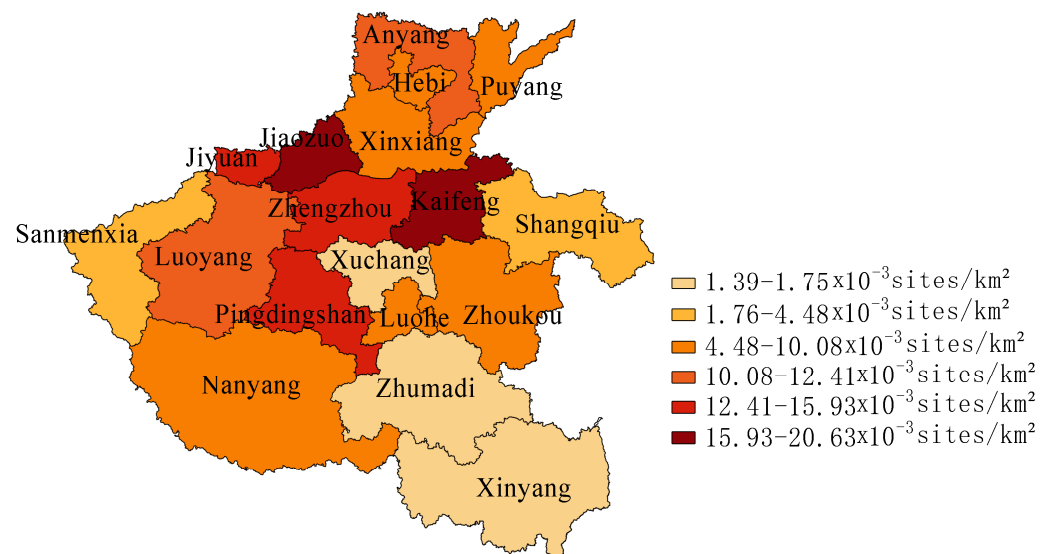
SBH in Henan presents a spatial-distribution pattern summarized as “one core, two belts, multiple poles”. SBH sites are primarily distributed along the western edge of the Huang-Huai-Hai Plain and the northern part of the Nanyang Basin, while the Funiu Mountains in western Henan and the Dabie Mountains in southern Henan show an overall sparse distribution (Figure 4).

The distribution centers on Zhengzhou and Luoyang, covering cities such as Pingdingshan and Xuchang. The heritage density in these areas is significantly higher than in other regions, which aligns closely with their status as regional transportation hubs and major industrial bases. Furthermore, this core area is located in the piedmont plain zone with relatively low meteorological disaster risk, providing a stable environmental founda-

tion for large-scale industrial construction, the implementation of major projects, and the preservation of heritage from the socialist construction period.

The northern and western Henan corridors form secondary agglomeration belts extending outward from both sides of the core area. The region encompassing Anyang, Xinxiang, and Jiaozuo in northern Henan saw an early start to modern industry, possesses excellent mineral resource endowments, and has hydrothermal conditions suitable for industrial development, resulting in a dense distribution of industrial heritage. In western Henan, Sanmenxia has formed a heritage cluster with clear functional orientations, relying on the construction of the Yellow River water conservancy project and the layout of the national defense industry.

The distribution of heritage in southern and eastern Henan plains is sparse, including areas such as Nanyang, Xinyang, Zhoukou, and Shangqiu. Although the terrain is flat, these regions experience heavy rainfall during the flood season and are prone to waterlogging. Consequently, the industrialization process and construction intensity are relatively low, leading to a small number and low density of heritage sites. As the central city of southwestern Henan, Nanyang exhibits a point-like distribution of heritage. However, the mountainous areas of western and southern Henan are characterized by high altitude and concentrated precipitation, which easily trigger disasters such as flash floods and landslides. Coupled with significant terrain relief and limited conditions for construction land, the distribution of SBH in these areas is extremely sparse.

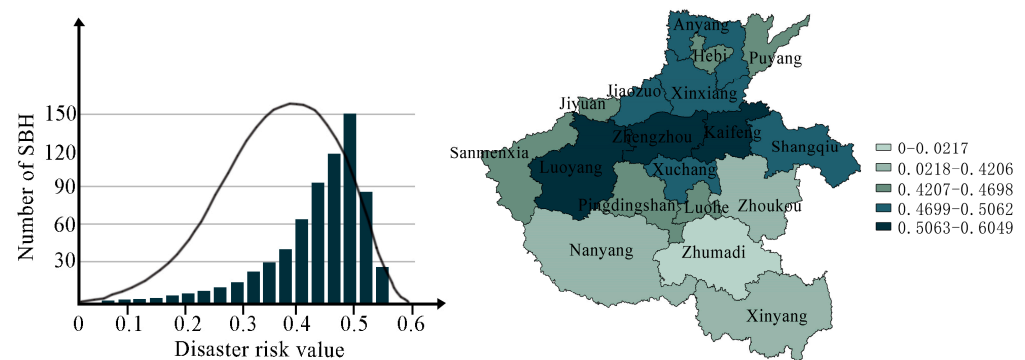


**Figure 4.** Density distribution map of SBH in Henan.

## 6.2. Disaster Risk Assessment of SBH in the Climatic Environment

### 6.2.1. Overall Risk Pattern

Calculated by Equation (3), the mean disaster-risk value is  $0.421 \pm 0.153$  for SBH in Henan. The risk data shows significant positive-skewed distribution: low-risk sites constitute the majority, while high-risk extreme values lift the overall level. Spatially, the distribution presents a distinct core–periphery structure, forming a pattern of high risk in the central-northern region and low risk in the southern region (Figure 5). This pattern strongly couples with Henan’s climatic environment, socioeconomic development level, and historical construction intensity.



**Figure 5.** Distribution map of positively skewed distribution and spatial heterogeneity of disaster risk for SBH in Henan.

The extremely high-risk areas are concentrated in Zhengzhou and Kaifeng. Although the hazard level of the ME factors in this region is not the highest, it acts as a key triggering factor. When superimposed with high exposure and high vulnerability, it results in persistently high disaster risk. The eastern Henan plain experiences a high number of days with extreme high temperatures and concentrated precipitation. This alternating humid and hot climate accelerates the weathering and decay of heritage sites. Furthermore, Kaifeng is located beneath the “suspended river” section of the Yellow River and faces potential flood threats, contributing to its high disaster risk value.

High-risk areas are distributed in a belt-like pattern along the alluvial plain, including cities such as Xinxiang, Xuchang, and Anyang. This zone represents a sensitive area for climatic disasters in Henan. Anyang and Xinxiang are situated in the piedmont zone of the Taihang Mountains in northern Henan, which serves as a superposition zone of the rainstorm convergence area induced by topographic lifting and the floodplain of the Yellow River. With the highest annual average wind speeds and the compound driving forces of meteorological and flood disasters such as strong winds and rainstorms, these cities face high compound ME risks.

Medium-risk areas include six cities, such as Shangqiu and Jiaozuo. Located in climatic transition zones, these cities are influenced by single meteorological factors and do not exhibit a multi-hazard superposition effect. With all environmental risk indicators at moderate levels, they function as a transition zone between high- and low-risk areas.

Lower-risk and extremely low-risk areas are distributed in southern Henan, including Xinyang and Zhumadian. Although this region has the highest annual precipitation and belongs to the high-value zone of  $H$ , it is predominantly characterized by mountains and hills. These landforms impede airflow, thereby reducing wind disaster risks. Additionally, the low density of heritage sites contributes to strong overall stability, keeping risk values at a low level.

#### 6.2.2. Threshold Effect of $H$

To reveal nonlinear threshold-driving effects of ME factors on heritage-disaster risk, we use the  $H$  index as the independent variable and the disaster risk value (Risk) as the dependent variable. Piecewise-regression and exponential-fitting approaches identify critical risk-mutation points and quantitative factor-correlation characteristics.

Taking hazard index 0.4 as the segmentation breakpoint, the Chow breakpoint test validates this critical threshold, with a 95% confidence interval [0.372, 0.428],  $p < 0.001$ . All samples were divided into a low-hazard segment ( $H \leq 0.4$ ) and high-hazard segment ( $H > 0.4$ ) for separate regression fitting.

##### (1) Low- $H$ segment ( $H \leq 0.4$ )

Heritage-disaster risk increases slowly and linearly with rising  $H$ . Fitted equation:

$$Risk = 0.312H + 0.205 \quad (5)$$

Coefficient of determination  $R^2 = 0.32$ . Weighted-average computation over segment samples indicates that for each 0.1 increment of  $H$ , disaster risk increases by approximately 8.5%. This reflects moderate driving capacity of ME factors under low-hazard conditions, consistent with gentle linear-growth fitting results.

## (2) High- $H$ Segment ( $H > 0.4$ )

In this segment, SBH disaster risk shows exponential growth under synergistic H-E-V interactions. Fitted formula:

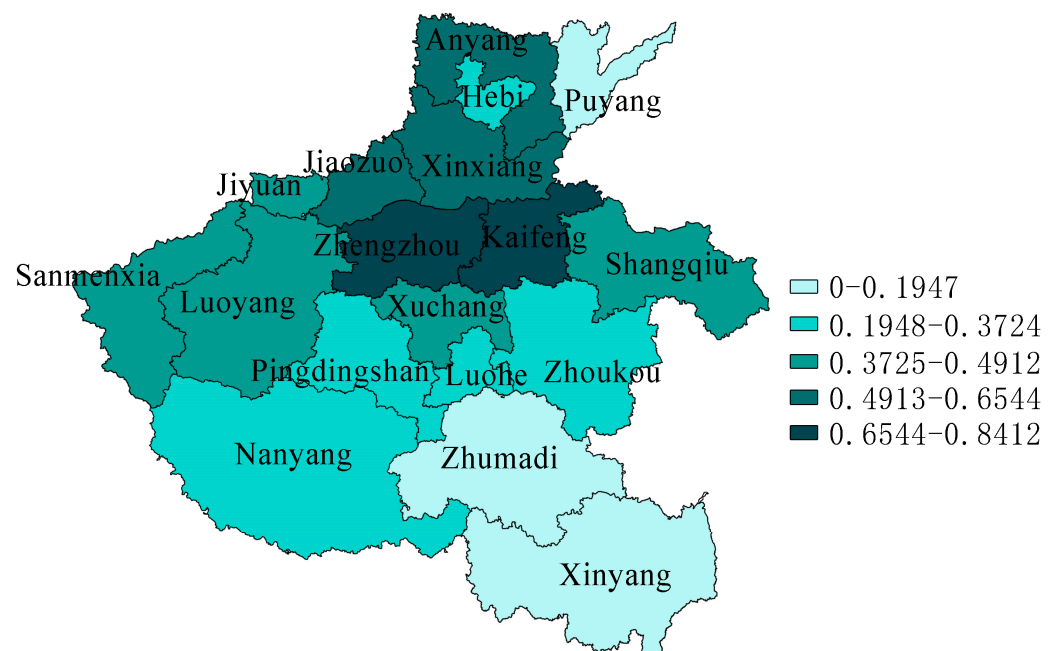
$$Risk = k \cdot e^{\lambda(H \cdot E \cdot V)} \quad (6)$$

where  $k = 0.186$  (proportionality coefficient);  $\lambda = 1.23$  (risk-amplification coefficient).  $H \cdot E \cdot V$  denotes the coupling degree of hazard, exposure, and vulnerability, reflecting the intensity of their synergistic interaction.

When the H-E-V coupling term increases by 0.1, disaster risk rises by 31.6% on average, matching the exponential growth law of  $\lambda = 1.23$ . After  $H$  exceeds the critical threshold, exposure and vulnerability generate synergistic amplification effects that produce nonlinear exponential growth of disaster risk [27]. This threshold effect is most prominent in extremely high-risk cities Zhengzhou and Kaifeng, where mean  $H$  ranges from 0.42 to 0.51 (surpassing threshold 0.4). Driven by high-E and high-V synergies, local risk values are amplified 2.1–2.6-fold.

## 6.2.3. Spatial Characteristics of Multi-Type Meteorological Compound Disaster Risk

Meteorological hazards seldom act independently on SBH; flood, wind-erosion, temperature-humidity alternation, and rainfall-induced secondary geological hazards often interact and produce compound amplification effects. We synthesized multi-hazard overlapping intensity, heritage exposure, and vulnerability at the prefecture-city scale to map the integrated compound disaster risk (Figure 6).



**Figure 6.** Spatial distribution map of multi-type meteorological compound disaster risk for SBH in Henan.

Spatially, compound risk shows a pattern of “north-central high, southern low”.

The extremely high-risk zone is concentrated in Zhengzhou and Kaifeng. Superimposed short-duration heavy rainfall, frequent wet–dry alternation, and Yellow River flood pressure couple with dense high-exposure SBH clusters, triggering significant compound structural damage.

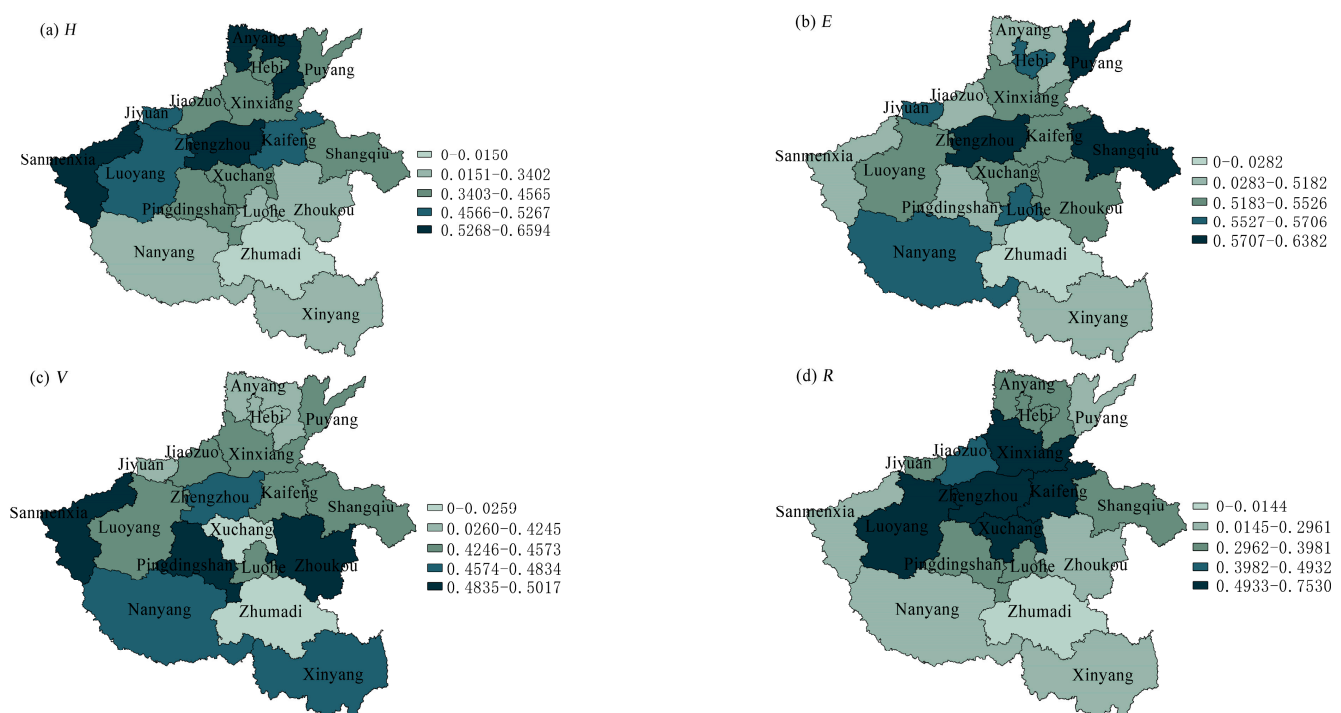
The high-risk zone forms a continuous Taihang piedmont belt covering Anyang, Xinxiang and Jiaozuo. Wind-erosion and orographic rainstorm hazards overlap here; open-air industrial heritage faces combined threats of wind abrasion and water-induced foundation instability.

The medium-risk zone includes Luoyang, Xuchang, Shangqiu, and Sanmenxia. Dominated by single meteorological hazards, the probability of simultaneous multi-hazard outbreaks remains limited, and overall compound risk stays at a moderate level.

The relatively low-risk zone involves Pingdingshan, Luohe, and Zhoukou. Although affected by local rainstorm waterlogging, heritage vulnerability and hazard superposition degree are restrained, without obvious multi-factor synergistic amplification.

The low-risk zone is mainly distributed in southern Henan (Xinyang, Zhumadian). Despite high annual precipitation, low gale frequency and sparse SBH distribution restrict compound disaster consequences.

Notably, compound risk does not fully coincide with the single H-dimension spatial distribution. Several mountainous cities with high meteorological hazard do not reach extremely high compound risk, constrained jointly by exposure, vulnerability, and resilience. This further confirms that heritage disaster risk is a coupled outcome of H-E-V-R rather than controlled by hazard intensity alone. Figure 7 provides spatial reference for multi-hazard early-warning and differentiated conservation of SBH.



**Figure 7.** Distribution map of disaster risk of SBH by dimension in different cities of Henan.

### 6.3. Spatial Patterns of Dimensional Elements of Disaster Risk in SBH Under ME Influence

To reveal the formation mechanism of disaster risk, a visualization analysis of the disaster risk for SBH in Henan was conducted from the four dimensions of H, E, V, and R. This analysis clearly presents the spatial differentiation characteristics of each dimension.

## (1) H

The spatial differentiation of *H* in Henan is significant, showing a distribution pattern that is high in the west and north but low in the east and south (Figure 7a). Sanmenxia ( $H = 0.6594$ ) and Anyang ( $H = 0.6318$ ) have the highest indices.

## (2) E

*E* exhibits a centripetal distribution along rivers and transportation routes. Shangqiu ( $E = 0.6382$ ) and Luohe ( $E = 0.5706$ ) are located in the old course of the Yellow River and the Huaihe River basin (Figure 7b).

## (3) V

*V* is determined by construction age and material. In old industrial and agricultural bases such as Pingdingshan ( $V = 0.4943$ ), Zhoukou ( $V = 0.4922$ ), and Sanmenxia ( $V = 0.5017$ ). Cities like Xuchang ( $V = 0.3921$ ) and Hebi ( $V = 0.3998$ ) have lower vulnerability (Figure 7c).

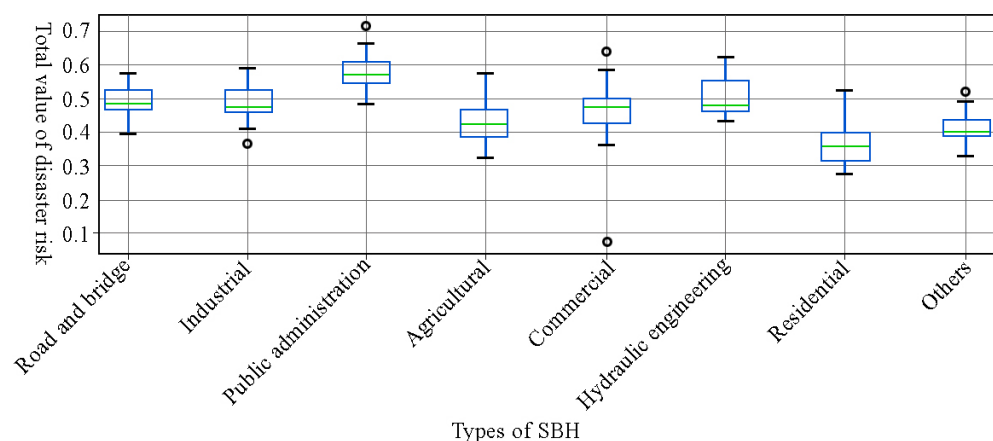
## (4) R

*R* is positively correlated with vegetation coverage and fiscal investment. As the economic and cultural centers of Henan, Zhengzhou ( $R = 0.7520$ ), Kaifeng ( $R = 0.7232$ ), and Luoyang ( $R = 0.6894$ ) benefit from higher fiscal investment, perfect protection management institutions, and higher green space ratios. Zhoukou ( $R = 0.2727$ ) and Zhumadian ( $R = 0.0144$ ) are weak links in risk governance (Figure 7d).

Random forest factor contribution rate was calculated; extreme precipitation (32.7%) and annual strong wind days (28.1%) ranked as the top two dominant meteorological driving factors with statistical support.

#### 6.4. Response Sensitivity of Different SBH Types to ME Factors

Different types of SBH exhibit distinct functional differentiation in their response mechanisms to *E* factors due to variations in function, structure, and spatial location. Consequently, there are significant differences in disaster risk levels (Figure 8).



**Figure 8.** Distribution characteristics of disaster risk values for various types of SBH.

Public administration (Mean Risk = 0.516) and commercial (Mean Risk = 0.420) heritage types belong to the high-sensitivity category regarding ME factors. Located mostly in urban core areas with high rates of surface hardening, they are affected by the urban rain island effect, which amplifies the risk of rainstorm waterlogging. Their risk values show a strong positive correlation with precipitation intensity.

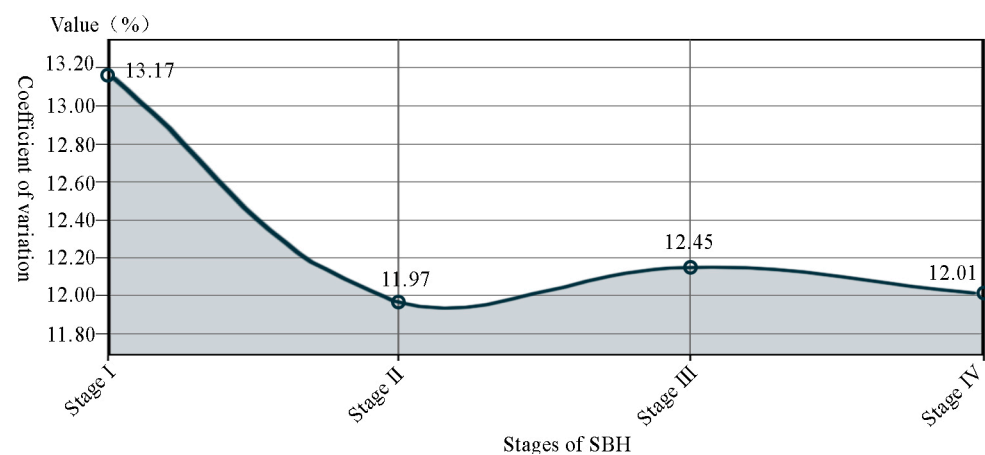
Industrial (Mean Risk = 0.488) and hydraulic engineering (Mean Risk = 0.480) heritage types belong to the high-hazard-bearing category, exhibiting relatively high disaster risk

levels. Industrial heritage is mostly distributed on river valley terraces at urban edges, often accompanied by issues such as structural aging. Furthermore, as some are located in areas prone to geological hazards, wind loads and foundation settlement are the main disaster-causing factors. Hydraulic engineering structures are directly exposed to extreme hydrological cycles, and their risk levels are primarily controlled by the fluctuation range of flood levels.

Agricultural (Mean Risk = 0.374) and residential (Mean Risk = 0.306) heritage types have relatively low disaster risks. This is mainly attributed to spontaneous maintenance behaviors by residents and the discrete distribution of such buildings, which enables them to exhibit strong social and R during meteorological disasters.

#### 6.5. Temporal-Evolution Characteristics of SBH Disaster Risk Across Four Construction Stages

Retrospective simulation for the four construction stages demonstrates that SBH disaster risk across historical phases presents an evolutionary trend of overall convergence with stable spatial structure. The CVs for the four stages are sequentially 13.17%, 11.97%, 12.45%, and 12.01%, showing a continuous declining tendency (Figure 9).

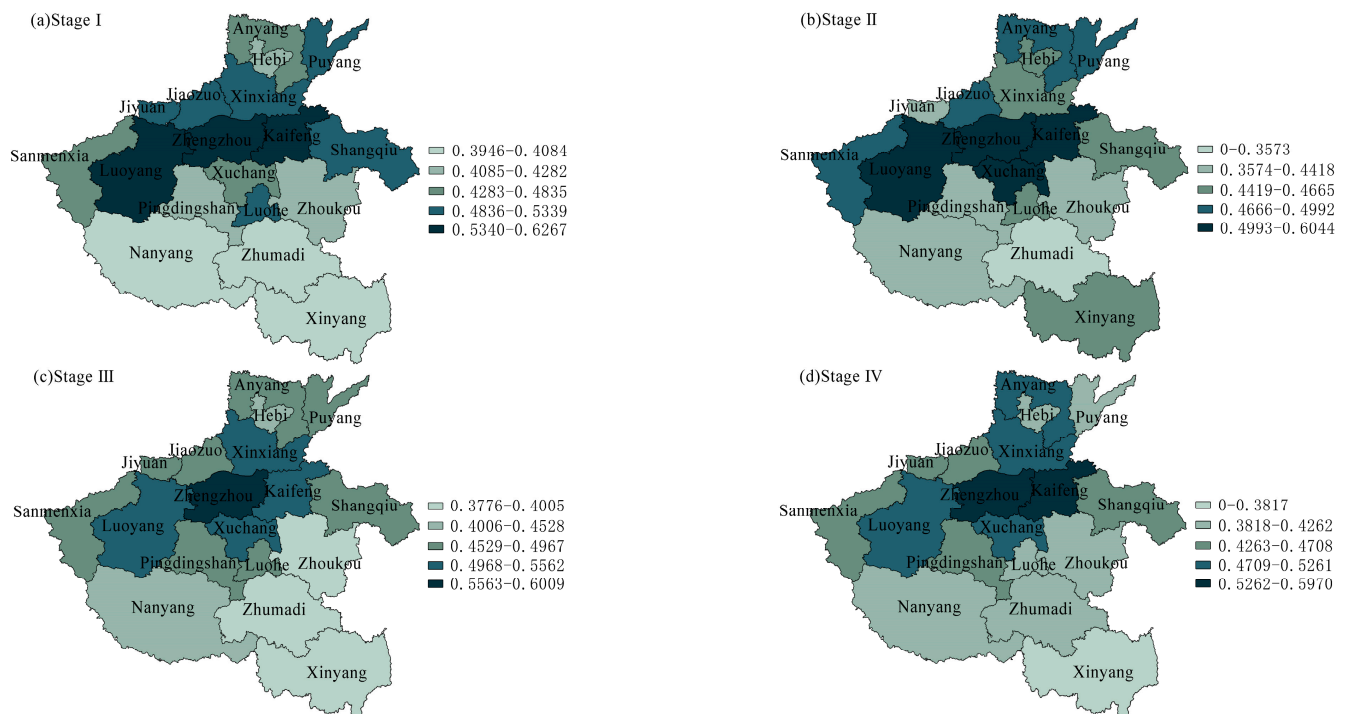


**Figure 9.** Heterogeneity coefficients of disaster risk for SBH at different stages.

This trend arises because early-period SBH was constrained by random site-selection practices and technical limitations, creating large risk disparities. Large-scale later-stage industrial construction drove homogenization of heritage attributes and more balanced risk distribution. Progress in construction technology, especially upgraded seismic-fortification standards and improved meteorological-monitoring-early-warning capacity, shifted heritage-system responses to ME conditions from high vulnerability toward low sensitivity, promoting risk-distribution convergence.

Although the heterogeneity of disaster risk has declined, high-risk areas remain concentrated in the central region with Zhengzhou as the core, exhibiting a stable core-periphery pattern. Core cities in the region were the focus of construction throughout the socialist construction period. The regional natural geographical background serves as a deep-seated rigid constraint controlling the spatial differentiation of heritage risk. This constraint transcends technological improvements across the temporal dimension, endowing the heritage stock and the associated risk pressure in core areas with significant continuity.

In the first stage, risk differentiation initially emerged with significant spatial agglomeration, and a core-periphery pattern began to take shape (Figure 10a). Zhengzhou (Risk = 0.6267) had the highest disaster risk value, followed by Kaifeng (Risk = 0.5817) and Luoyang (Risk = 0.5533), forming a high-risk agglomeration area centered in the central region. Nanyang had the lowest risk (Risk = 0.3946). The gap between cities reached 0.2321, indicating significant risk differentiation.



**Figure 10.** Spatial distribution of disaster risks of SBH at various stages in different cities.

In the second stage, the risk pattern underwent reorganization. Risk levels concentrated towards the medium-high range and tended to become centralized (Figure 10b). Zhengzhou maintained the highest risk value (Risk = 0.6044), while the risk in Xuchang rose substantially (Risk = 0.5472), and the risk in Shangqiu decreased significantly (Risk = 0.4513).

In the third stage, construction fluctuated, and the trend of risk polarization rebounded, with medium-risk cities accounting for 66.7% (Figure 10c). The risk in Xinxiang increased by 0.0548, returning to the high-risk category, while the risk in Xinyang decreased by 0.0598, leading to a lower risk level.

In the fourth stage, the layout tended to disperse, and risk further converged. The number of low-risk cities increased, the average risk value dropped to 0.4620, and low-risk cities accounted for 44.4% (Figure 10d). The risk value in Zhengzhou decreased to 0.5970, and the risk in Luohe dropped significantly by 0.0642. The overall risk level declined notably, showing a clear convergence trend.

## 7. Discussion

This study employs a multi-hazard spatial differentiation analytical framework consistent with mainstream paradigms for architectural heritage disaster risk assessment in China and Europe. Building on this established theoretical basis, this work improves existing research in framework construction, research object refinement, quantitative methods, and disaster mechanism interpretation while elaborating the model limitations and viable future research directions.

Conventional heritage risk assessment relies predominantly on the static H-E-V framework, which ignores systemic buffering and adaptive capacity and may cause biased risk estimation. This study addresses this drawback by integrating system resilience to construct an optimized H-E-V-R coupled evaluation model. The revised multi-dimensional framework incorporates both ecological regulation and social mitigation capacity, enabling a more comprehensive and realistic quantification of heritage disaster-bearing characteristics. Furthermore, most existing studies focus on ancient stone buildings or general industrial heritage, while risk research on modern architectural heritage remains inadequate. This

paper targets brick–concrete and brick–wood special SBH constructed from 1949 to 1978 and conducts stratified risk analysis based on construction stages and functional attributes. This refined research scope fills the current research gap and enhances the targeted practical value of findings for modern heritage conservation.

Methodologically, prior heritage disaster studies rely heavily on qualitative analysis and empirical inference, with rare quantitative identification of the nonlinear threshold effects of meteorological hazards. Using piecewise regression, this study identifies the critical threshold of meteorological–environmental factors and validates their statistical significance, achieving quantitative characterization of meteorological disaster impacts on heritage. The results demonstrate that meteorological–environmental factors drive SBH disaster risk through distinct nonlinear threshold amplification rather than linear superposition. When the meteorological hazard index exceeds 0.4, heritage risk increases exponentially with exposure and vulnerability ( $R^2 = 0.78$ ). This phenomenon is prominent in high-risk areas including Zhengzhou and Kaifeng, revealing a complete disaster chain: extreme precipitation induces soil erosion, undermines foundation stability, and ultimately triggers structural collapse. These findings quantitatively verify the feasibility of applying disaster-chain theory to heritage risk assessment and conservation [28].

The introduced resilience factor  $R$  effectively corrects the systematic risk overestimation of traditional static models, acting as a core damping coefficient for heritage systems against meteorological disasters. Vegetation coverage contributes to rainfall interception and soil consolidation, mitigating foundation erosion under extreme weather. Meanwhile, sophisticated urban emergency management systems convert meteorological early warnings into targeted mitigation measures, reducing actual heritage losses [29]. For example, despite high meteorological hazard exposure in Zhengzhou, robust ecological resilience buffers the theoretical heritage risk value by 23.6%, confirming the crucial regulatory role of systemic resilience in balancing regional disaster risk.

Although the H-E-V-R model effectively explains the spatial differentiation of SBH disaster risk across Henan Province, several limitations persist. First, the fixed-resolution meteorological data fails to capture site-scale microclimate variations and micro-meteorological impacts, potentially causing local assessment deviations. Second, heritage material aging parameters in the model are empirically estimated without support from long-term in situ monitoring data, limiting simulation accuracy.

### 7.1. Limitations of the Study

This H-E-V-R coupling model can well explain the spatial differentiation of SBH meteorological disaster risk in Henan, but three obvious research limitations remain:

- (1) Meteorological data resolution limitation: The 30 m unified raster meteorological dataset cannot capture microclimate differences of a single heritage building site (valley micro-wind field, building enclosure local humidity), so the micro-scale meteorological erosion mechanism cannot be precisely simulated.
- (2) Heritage material aging parameter deficiency: The current building-aging coefficient adopts an empirical exponential formula, lacking long-term continuous field-monitoring data of brick, concrete, and wood-material weathering degradation to calibrate model parameters.
- (3) Spatial-scale constraint: This study only performs risk-aggregation analysis at the prefecture-city scale and cannot realize fine risk zoning for individual heritage sites.

### 7.2. Future Research Directions

Introduce CFD computational-fluid-dynamics simulation to model micro-wind and humidity fields around heritage buildings. Conduct multi-year on-site monitoring of material

aging to optimize the vulnerability index calculation. Combine high-precision micro-spatial datasets to achieve fine-scale disaster-risk mapping for individual heritage sites.

## 8. Conclusions

### 8.1. Main Research Conclusions

This study takes 1362 SBH sites in Henan as the research object and constructs an H-E-V-R multi-dimensional coupling risk assessment model. It quantitatively reveals the spatial differentiation mechanism of disaster risk for SBH driven by meteorological–environmental factors. The main conclusions are as follows:

- (1) The disaster risk of SBH in Henan is controlled by the coupling of meteorological, geological, and human-related environmental factors, showing a spatial pattern of high risk in the central-northern region and low risk in the southern region. Zhengzhou and Kaifeng are core agglomeration zones of heritage disaster risk, closely associated with alluvial-plain topo-geological conditions of the Yellow River and monsoon-driven precipitation.
- (2) Extreme precipitation and annual strong-wind days are the dominant meteorological–environmental factors shaping risk spatial differentiation. Their destructive effects are amplified by nonlinear interactions between exposure and vulnerability. The hazard index value of 0.4 represents the critical threshold for abrupt heritage-disaster-risk growth. Different heritage types show heterogeneous responses to meteorological hazards; public-administration heritage exhibits the highest sensitivity to flood hazards.
- (3) Resilience (R) exerts a critical buffering effect that mitigates meteorological-disaster damage to heritage. As construction periods advance, improved building-construction standards and local management capacity enhance the heritage system’s adaptability to meteorological environments, driving risk convergence toward lower heterogeneity and lower sensitivity.
- (4) Disaster-risk levels differ substantially across heritage functional types. Public-administration and commercial heritage located in high-exposure urban cores suffer prominent rain-storm waterlogging threats and yield higher risk values. Residential heritage maintains relatively low disaster risk due to strong social adaptability and spontaneous self-maintenance.

This study provides a scientific reference for targeted disaster prevention–mitigation and evidence-based conservation for Henan’s SBH. It delivers a generalizable quantitative model and workflow for applying meteorological–physical theories within cultural-heritage risk assessment, supporting interdisciplinary integration between heritage conservation and atmospheric–environmental science.

### 8.2. Adaptive Conservation and Mitigation Suggestions

Based on risk zoning, functional-type differences, and temporal-evolution characteristics of SBH disaster risk, classified and zoned adaptive-conservation suggestions are proposed:

- (1) Core high-risk area (Zhengzhou, Kaifeng): Establish a real-time meteorological early-warning platform targeting rain-storm and gale hazards. Strengthen wall waterproofing and foundation anti-settlement structures for brick–concrete public-administration heritage. Construct riparian buffer green space to improve regional ecological resilience.
- (2) Northern belt-shaped medium-to-high-risk cities (Anyang, Xinxiang, Jiaozuo): Implement wind-erosion protection for open-air industrial heritage; plant wind-break vegetation along Taihang piedmont zones. Monitor material deterioration induced by seasonal wet–dry alternation for brick–wood workshop buildings.

- (3) Southern low-risk mountainous area (Xinyang, Zhumadian): Prioritize compound geo-meteorological hazard (flash flood, landslide) monitoring for scattered agricultural and hydraulic-engineering heritage. Preserve natural vegetation coverage to sustain ecological resilience.
- (4) Type-differentiated conservation measures: Perform regular waterproof-drainage maintenance for flood-sensitive public-administration and commercial heritage. Reinforce wind-load resistance for industrial and hydraulic-engineering heritage. Preserve residents' spontaneous maintenance mechanisms for residential heritage to leverage social-resilience benefits.
- (5) Phase-oriented adaptive renovation: Carry out comprehensive structural safety inspection for aging heritage from Stage I (1949–1952). For post-Third-Front-construction Stage IV heritage, optimize meteorological-disaster-prevention auxiliary facilities based on original building structures and avoid large-scale reconstruction.

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## Abbreviations

The following abbreviations are used in this manuscript:

|     |                              |
|-----|------------------------------|
| SBH | Socialist-Built Heritage     |
| H   | Hazard                       |
| E   | Exposure                     |
| V   | Vulnerability                |
| R   | Resilience                   |
| VIF | Variance Inflation Factor    |
| ME  | Meteorological–Environmental |

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