sustainability

MDPI

Article

Study on Flood Resilience Based on the DPSIR Framework from the "Engineering–Ecological–Management" Perspective: A Case Study of Zhejiang Province

Wei Dai [1,*], Xijun Hou [2] and Steffen Nijhuis [3]

[1] School of Spatial Planning and Design, Hangzhou City University, Hangzhou 310015, China
[2] School of Art and Archaeology, Hangzhou City University, Hangzhou 310015, China; 2261003031@stu.hzcu.edu.cn
[3] Department of Urbanism, Delft University of Technology, 2628BX Delft, The Netherlands; s.nijhuis@tudelft.nl
* Correspondence: daiwei@hzcu.edu.cn

Abstract

Against the backdrop of global climate change and rapid urbanization, extreme rainstorm events have become increasingly frequent, and urban–rural flood risk has continued to intensify, rendering flood resilience an essential concern for sustainable urban and rural development. To address the serious homogenization of existing indicator systems, the unclear associations among cross-dimensional factors, and the weakness of spatial-differentiation research in current flood resilience evaluations, this study builds a flood resilience evaluation indicator system for Zhejiang Province containing 18 indicators from the "Engineering-Ecological-Management" (EEM) perspective, based on the "Driving-Pressure-State-Impact-Response" (DPSIR) framework. A combined weighting method integrating the entropy weight (EW) and the analytic hierarchy process (AHP) is used to determine indicator weights, and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is applied to evaluate the Flood Resilience Index (FRI) of 11 cities in Zhejiang Province from 2004 to 2024. The Barrier Degree Model (BDM) is adopted to identify the critical obstacle factors affecting the improvement of flood resilience, and the grey relational analysis (GRA) method is applied to analyze the correlation among engineering, ecological and management factors. The results show that: (1) from 2004 to 2024, the provincial average FRI of Zhejiang Province rose from 0.1657 to 0.5021, with a growth rate of 203.09%, exhibiting an evolutionary pattern of "comprehensive improvement with accelerated growth in the later stage"; (2) in 2024, the spatial pattern of FRI presents a hierarchical agglomeration characteristic of "Fifth grade leading, Fourth grade contiguous, and Third grade dispersed": Hangzhou, Wenzhou, and Quzhou attain fifth grade flood resilience, Zhoushan remains at third grade, and the other cities are at fourth grade. From 2004 to 2024, the inter-city FRI gap follows an inverted-V trajectory of "large-small-large"; (3) The evolution of the key barrier factors is highly consistent with the different stages of flood management in Zhejiang, having passed through three phases: bridging shortcomings in engineering infrastructure, advancing "engineering and ecology" in tandem, and widening engineering gaps superimposed with new barrier factors. The "maximum pumping and drainage capacity of pumping stations and pipe networks" has consistently ranked as the primary barrier factor; and (4) the pairwise correlations among the engineering, ecological, and management dimensions are differentiated: the "engineering-management" correlation is the highest (0.7957), the "engineering-ecological" correlation is intermediate (0.7488), and the "ecological-management" correlation is the lowest (0.7051), indicating that coordination between green infrastructure and the management system remains weak as flood resilience improves. On this basis, this study proposes differentiated flood resilience

Check for updates

Academic Editor: Wen Cheng Liu

Received: 15 August 2026
Revised: 22 September 2026
Accepted: 28 September 2026
Published: 2 October 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

improvement strategies for cities in Northern, Eastern, Southern, and Western Zhejiang from the three aspects of engineering defense, ecological restoration, and management coordination, providing decision-making support for the construction of flood-resilient cities.

Keywords: flood resilience evaluation; DPSIR model; cross-dimensional relationship; dynamic evolution; climate change

1. Introduction

Against the backdrop of global climate change, extreme rainfall events occur with increasing frequency. Rapid urbanization has further given rise to environmental problems such as the shrinkage of ecological space, causing urban–rural flood risk to intensify continuously. According to the 2025 China Flood and Drought Disaster Prevention Bulletin issued by the Ministry of Water Resources of the People's Republic of China, in 2025 the number of flood disasters, the number of deaths and missing persons, and the direct economic losses accounted for 76.59%, 78.73%, and 75.50%, respectively, of the corresponding totals of all natural disasters nationwide in that year [1]. Flood disasters have seriously threatened the lives and property of the public and the normal operation of cities, and have become a major constraint on resilient urban development.

As the core of sustainable urban development, flood resilience has attracted increasing attention [2–4]. Improving flood resilience is a systematic undertaking that encompasses pre-disaster prevention, during-disaster response, and post-disaster recovery. This requires urban and rural spaces to possess strong resistance, rapid response, and self-repair capacity in the face of flood disasters [5–10]. Existing studies on flood resilience evaluation mostly cover the dimensions of infrastructure, economic foundation, and social governance. For example, infrastructure resilience reflects the engineering capacity to resist flood disasters [11–13]; ecological resilience reflects the flood regulation and storage capacity [14,15]; economic resilience reflects the redundancy and flexibility of the urban–rural economy in the face of floods [16,17]; and social resilience reflects the capacity of social organization and coordination when cities and rural areas confront floods [18]. Core resilience capabilities such as robustness, redundancy, resourcefulness, and rapidity have been proposed [18], together with multi-dimensional flood resilience measurement indicators based on "infrastructure, ecological environment, economic vitality, social capital, institutional governance, and community capacity" [19–22].

The "Driving-Pressure-State-Impact-Response" (DPSIR) model is an improvement upon the "Pressure-State-Response" (PSR) model; it was first proposed by the Organisation for Economic Co-operation and Development (OECD) in 1993 [23,24]. In 1994, the United Nations Environment Programme (UNEP) began to apply it to multiple fields such as water resources management, marine protection, and climate change. In 1999, the European Environment Agency (EEA) formally adopted the DPSIR model and promoted its application in environmental assessments across European countries [25]. The DPSIR model reveals the interactions among human beings, society, economy, resources, and the environment, and, as a core tool for studying disaster formation mechanisms, assessing system resilience, and optimizing response strategies, has been widely applied [26]. For instance, Lewison et al. applied the DPSIR model to identify drivers and pressures in coastal domains [27]; Lin et al. employed it to analyze the spatiotemporal changes in the ecological structure and functions of coastal wetlands [28]; Zhang et al. used the DPSIR model to conduct a comprehensive ecological risk assessment of the Guangxi region under different decision-making risks [29]; Sobhani et al. applied it to evaluate the ecological security of protected areas [30]; Chen

et al. used it to reveal the ecological civilization construction index across 30 provinces of China [31]; Cui et al. conducted an ecological security assessment of the Yangtze River Delta urban agglomeration in China based on the DPSIR model [32]; Wang et al. combined the DPSIR model to predict changes in regional water environmental carrying capacity from 2020 to 2030 [33]; Jiao et al. investigated the dynamic evolution of provincial-level resilience in China based on the DPSIR model [34]; Li et al. established an ecological security evaluation indicator system for the Hai River basin based on the DPSIR model [35]; Wang et al. evaluated the resilience of the water supply system in Zhengzhou based on the DPSIR framework [36]; Fang et al. applied the DPSIR model to study transportation resilience under extreme flood scenarios [37]; and Yuan et al. constructed an evaluation system for urban pluvial flood defense capacity based on the DPSIR model [38].

Nevertheless, existing flood resilience evaluation studies still suffer from important limitations. First, the evaluation indicators are seriously homogenized: on the one hand, evaluation factors are redundant; on the other hand, the natural geographical characteristics of specific regions and local flood management measures are not adequately reflected in the evaluation factors. Second, the analysis of barrier factors affecting flood resilience mostly remains at the level of single-indicator barrier-degree calculation and fails to reveal the cross-dimensional relationship among factors of "engineering-ecology-management". Third, the differentiated analysis of the spatial pattern of flood resilience is weak, and associations of key elements behind flood resilience have not been deeply examined.

Based on the above considerations, this study addresses three research questions: (1) How can the homogenization limitation of existing indicator systems be overcome, and an "Engineering-Ecological-Management" flood resilience evaluation indicator system that fits local characteristics be constructed? (2) How can the association patterns of key elements shaping the spatial pattern of flood resilience be revealed, the cross-dimensional relationships among factors of "engineering-ecology-governance" affecting the achievement of flood resilience be clarified, and the dynamic evolution of key factors at different development stages be explored? (3) How can tailored, differentiated flood resilience improvement paths be proposed on the basis of the current status and regional characteristics of urban flood resilience?

Based on the DPSIR framework and taking Zhejiang Province as the study area, this study investigates the spatiotemporal evolution of flood resilience in Zhejiang Province, with the following main objectives: (1) to construct an "Engineering-Ecological-Management" (EEM) flood resilience evaluation indicator system tailored to local characteristics; (2) to examine the spatiotemporal evolution of flood resilience across 11 cities in Zhejiang Province, China, from 2004 to 2024; (3) to reveal the key factors affecting flood resilience improvement and their hierarchical association by combining the BDM with GRA; and (4) to propose differentiated flood resilience improvement countermeasures for different regions. The results offer a referable evaluation framework and governance paradigm for understanding the evolution of flood resilience and the association of barrier factors from the EEM perspective, and provide scientific support and typical cases for flood resilience evaluation, carrying important theoretical and practical significance.

2. Study Area, Framework, and Methods

2.1. Study Area

The study area comprises 11 cities under the jurisdiction of Zhejiang Province, China: Hangzhou, Ningbo, Wenzhou, Jiaxing, Huzhou, Shaoxing, Jinhua, Quzhou, Zhoushan, Taizhou, and Lishui, with a total area of 105,500 km^2 and a permanent resident population of 66.70 million at the end of 2024; the gross domestic product (GDP) reached 9.0131 trillion yuan.

Zhejiang Province is located on the southeastern coast of China, on the southern wing of the Yangtze River Delta, bordering the East China Sea to the east. Its total coastline is 6715 km (including island shorelines), of which the mainland coastline is 2200 km. It adjoins Fujian to the south, Jiangxi and Anhui to the west, and Shanghai and Jiangsu to the north. Its terrain is characterized by "seven parts mountain, one part water, and two parts farmland". The provincial average annual rainfall is about 1500 mm, with an annual total precipitation of 160–170 billion m^3; precipitation is unevenly distributed in time and space. The annual rainfall in Southern Zhejiang can reach 1800–2200 mm, while that in Northern Zhejiang is about 1200–1400 mm (Figure 1).

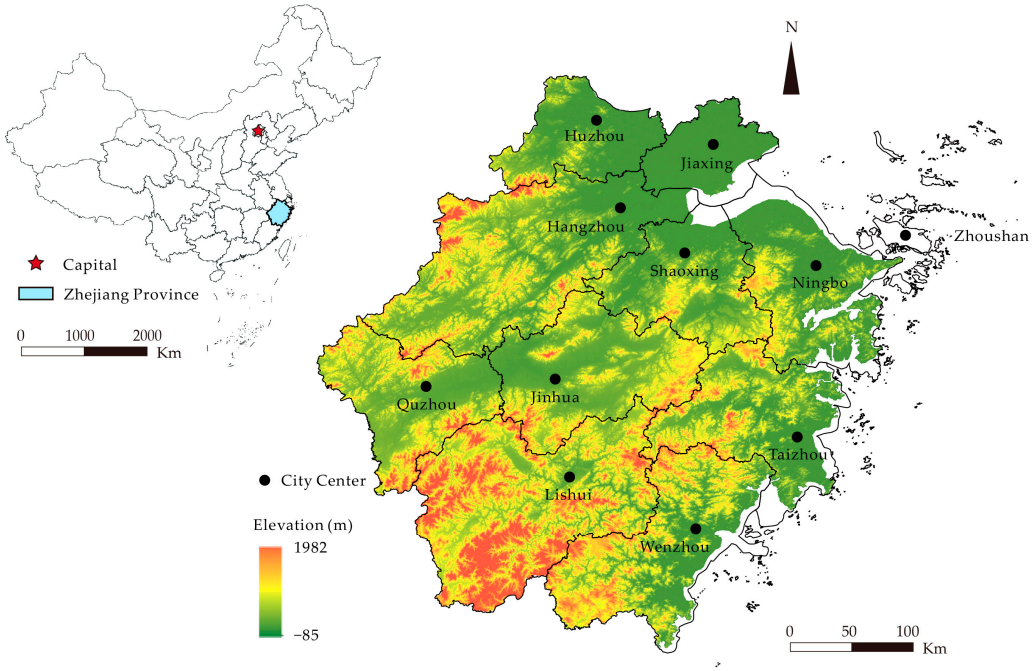


Figure 1. Study area.

Over the past two decades, affected by typhoons and extreme rainfall, major flood events have occurred frequently in Zhejiang Province. In 2015, Typhoon Chan-hom made landfall, and 69 counties (cities and districts), including Zhoushan, Ningbo, Shaoxing, and Taizhou, experienced urban waterlogging; the rain-gauge rainfall in Yuyao, Xiangshan, and Shangyu exceeded 200 mm, with severe ponding in urban and rural areas. In 2019, Typhoon Lekima made landfall; most of the main urban area of Linhai was submerged, and Ximen Station on the Lingjiang River recorded a historically high flood level of 10.98 m; severe urban waterlogging also occurred in Ningbo, Wenzhou, and many other places. In August 2020, Typhoon Hagupit made landfall, and parts of Wenzhou and Taizhou suffered severe waterlogging, with roads inundated and houses damaged. In September 2025, Cangnan, Pingyang, Longgang, and Ruian in Wenzhou experienced an extremely heavy rainstorm, triggering severe waterlogging, road blockage, inundated houses, and flooding of underground garages. On 12 July 2026, Typhoon Bavi made landfall in Yuhuan, Taizhou, causing widespread heavy rain in central and southern Zhejiang, damaging power lines in many parts of Taizhou and Wenzhou, and producing urban–rural waterlogging. On 18 August, Typhoon Dolphin made landfall in Yueqing, Taizhou, with a provincial areal rainfall of 215 mm; heavy rain and flooding were prominent in Ningbo, Zhoushan, and Wenzhou. On 28 August, Typhoon Saddle made landfall in Yuhuan, Taizhou, bringing coastal gales and heavy rain, with repeated ponding in many areas.

As an economically developed province on the southeastern coast of China and a high-frequency flood-prone region, Zhejiang Province serves as a typical and representative

case for flood resilience research. In terms of natural endowment, Zhejiang lies in the subtropical monsoon climate zone, where the superposition of plum rain season and the typhoon season gives rise to frequent extreme rainfall, rapid runoff concentration, and insufficient flood regulation and storage space. In terms of socio-economic conditions, the urbanization rate of Zhejiang Province has reached 73.4%; given its highly concentrated population, the economic losses and social impacts of flood disasters are particularly pronounced. In terms of flood management practice, over the past two decades, Zhejiang has intensively built a backbone water network and implemented such distinctive measures as the "Anlan Seawall Thousand-Billion Project", "city-wide sponge city construction" and "beautiful river and lake initiative", thereby forming a flood management system with regional characteristics.

2.2. Research Framework

Based on the research questions and objectives, the research framework of this study is shown in Figure 2.

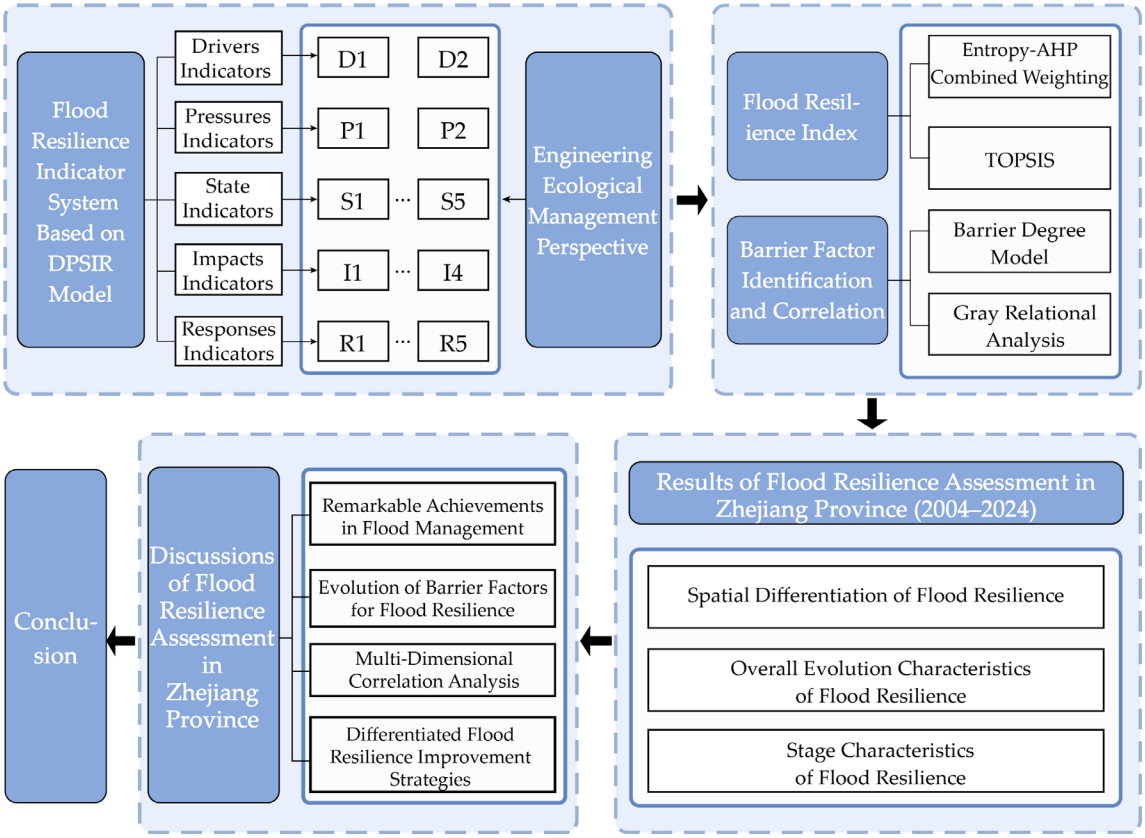


Figure 2. Research framework.

Step 1: Based on the DPSIR framework and from the EEM perspective, construct a DPSIR-based flood resilience evaluation indicator system for Zhejiang Province, and standardize the raw data.

Step 2: Adopt a combined weighting method that integrates the entropy weight (EW) and the analytic hierarchy process (AHP) to determine the combined weight of each evaluation indicator: the EW mines objective weights based on the dispersion of indicator data, while the AHP obtains subjective weights based on the judgment of domain experts; a robustness index is used to determine the importance of objective and subjective weights in the combined weight.

Step 3: Apply the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) to evaluate the Flood Resilience Index (FRI) of 11 cities in Zhejiang Province for five key years from 2004 to 2024, portraying the flood resilience level of each city in each year.

Step 4: Analyze the flood resilience evolution of the 11 cities from both temporal and spatial dimensions: in the temporal dimension, examine the evolution trend of the FRI of each city in different periods from 2004 to 2024; in the spatial dimension, reveal the spatial differentiation characteristics of the FRI and identify the spatial agglomeration pattern of high-value and low-value FRI areas.

Step 5: Introduce the barrier degree model (BDM) to identify and rank the key barrier factors restricting flood resilience improvement for each city in different years, quantifying the blocking effect of each indicator on flood resilience; and adopt the gray relational analysis (GRA) method to reveal the correlation intensity among the engineering, ecological, and management dimensional indicators in each year.

Step 6: Based on the causes of spatial differentiation and the diagnosis of barrier factors, propose targeted flood resilience improvement strategies for cities in Northern, Eastern, Southern, and Western Zhejiang from the three dimensions of engineering defense, ecological restoration, and management coordination, and distill the main conclusions of this study, so as to provide decision-making support for flood disaster management and resilient city construction.

2.3. Research Methods

2.3.1. Construction of a DPSIR-Based Flood Resilience Evaluation Indicator System for Zhejiang Province from the EEM Perspective

This study systematically searched the English literature published from 2000 to 2025 in the Web of Science (WoS) database. The search strategy was set as: TS = (flood resilience OR rainstorm waterlogging resilience OR urban resilience OR resilient city OR coastal city flood resilience) AND TS = (evaluation indicator system OR index system OR comprehensive evaluation model OR evaluation framework), yielding 191 relevant English papers. Meanwhile, Chinese literature published in the same period was searched in the China National Knowledge Infrastructure (CNKI) database, using the Chinese search formula SU = (flood resilience OR stormwater resilience OR urban resilience OR coastal resilience OR resilient city) AND SU = (evaluation indicator system OR comprehensive evaluation OR evaluation model), which initially yielded 205 Chinese core papers.

The retrieved Chinese and English literature was further screened. In the first stage, titles and abstracts were comprehensively screened to exclude studies unrelated to flood resilience evaluation indicator systems; in the second stage, full-text review was conducted to retain studies with complete indicator systems, high citation influence, and strong regional representativeness.

Through the above two stages, 78 high-quality papers were selected, from which widely recognized flood resilience evaluation indicators were extracted. On this basis, following the principles of independence and data availability, and combining the engineering, ecological, and management characteristics of Zhejiang Province with local water governance features, a DPSIR-based [39,40] flood resilience evaluation indicator system for Zhejiang Province from the EEM perspective was further constructed, containing 18 indicators in total, namely 6 indicators for the engineering dimension, 6 for the ecological dimension, and 6 for the management dimension (Table 1, Figure 3), so as to ensure the scientificity and regional adaptability of the indicator system.

Table 1. DPSIR-based flood resilience evaluation indicator system for Zhejiang Province from the EEM perspective.

Factor	Connotation	Evaluation Indicator	No. j	EEM Dimension	Indicator Type	Unit
Driving (D)	Socio-economic development and rapid urbanization as drivers of flood risk	D1 Permanent resident population density	1	Management	Negative	persons/km^2
		D2 Proportion of impervious area to total area	2	Engineering	Negative	%
Pressure (P)	Climate change as pressure on flood risk	P1 Annual frequency of heavy precipitation events (≥50 mm/h)	3	Ecological	Negative	times/year
		P2 Annual number of storm surges exceeding the warning tide level	4	Ecological	Negative	times/year
State (S)	Carrying state of rainstorm and flood risk	S1 Proportion of green space to total area	5	Ecological	Positive	%
		S2 Regulation and storage volume of blue-green space	6	Ecological	Positive	100 million m^3
		S3 Compliance rate of river and seawall flood control standards	7	Engineering	Positive	%
		S4 Compliance rate of drainage pipe network design standards	8	Engineering	Positive	%
		S5 Density of flood disaster shelters	9	Engineering	Positive	units/km^2
Impact (I)	Impacts of flood disasters on urban–rural systems	I1 Proportion of the population affected by floods in the current year to total population	10	Management	Negative	%
		I2 Proportion of the area inundated by floods to total area	11	Ecological	Negative	km^2
		I3 Proportion of direct economic losses caused by floods to current-year GDP	12	Management	Negative	%
		I4 Post-disaster recovery time	13	Management	Negative	days
Response (R)	Various interventions to mitigate flood risk	R1 Proportion of cumulative restored blue-green space to total area	14	Ecological	Positive	%
		R2 Proportion of built sponge city area to total area	15	Engineering	Positive	%
		R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	16	Engineering	Positive	10^3 m^3/h
		R4 Establishment rate of the cross-departmental flood control and drainage linkage mechanism	17	Management	Positive	%
		R5 Proportion of special flood control and drainage expenditure to total fiscal expenditure	18	Management	Positive	%

The indicator type "positive" in Table 1 indicates that a larger indicator value denotes stronger flood resilience, whereas "negative" indicates that a smaller indicator value denotes stronger flood resilience. The rationale for selecting the above indicators is as follows.

(1) Driving factor (D)

The permanent resident population density of Zhejiang Province ranks among the highest nationwide, and its GDP ranks fourth nationally. A high population density implies higher exposure and vulnerability under the same flood event. The proportion of impervious surface is a product of rapid urbanization and affects rainwater infiltration capacity and surface runoff peaks. This study selects permanent resident population density (D1) and the proportion of impervious surface to total area (D2) as the driving force factors.

(2) Pressure factor (P)

Socio-economic development and rapid urbanization, superimposed on extreme climate change, further increase flood risk and amplify the losses caused by flood disasters. Zhejiang has a concentrated Meiyu period, and heavy precipitation events and storm surges exceeding the warning tide level are the main external pressures triggering urban waterlogging in the province. This study selects the annual frequency of heavy precipitation events (P1) and the annual number of storm surges exceeding the warning tide level (P2) as the pressure factors.

(3) State factor (S)

The state factors include the proportion of green space to total area (S1), the regulation and storage volume of blue-green space (S2), the compliance rate of flood control standards for rivers and seawalls (S3), the compliance rate of design standards for drainage pipe networks (S4), and the density of flood disaster shelters (S5). S1 and S2 reflect the ecosystem capacity to absorb floods. S3, S4, and S5 reflect, from the engineering dimension, the defense capacity of major embankments, the drainage standards of municipal infrastructure, and the layout of emergency shelters.

(4) Impact factor (I)

The impact factors include the proportion of the population affected by floods in the current year to the total population (I1), the proportion of the area inundated by floods to the total area (I2), the proportion of direct economic losses caused by floods to the GDP of that year (I3), and the post-disaster recovery time (I4).

(5) Response factor (R)

The response factors include the proportion of cumulative restored blue-green space to total area (R1), the proportion of built sponge city area to total area (R2), the maximum pumping and drainage capacity of pumping stations and pipe networks (R3), the establishment rate of the cross-departmental flood control and drainage linkage mechanism (R4), and the proportion of special flood control and drainage expenditure to total fiscal expenditure (R5).

2.3.2. Determination of Indicator Weights

Scientifically determining indicator weights is a prerequisite for ensuring the reliability of flood resilience evaluation results. The entropy weight method relies on data dispersion and tends to overlook expert experience, whereas the analytic hierarchy process (AHP) relies on the subjective judgment of experts and is prone to bias.

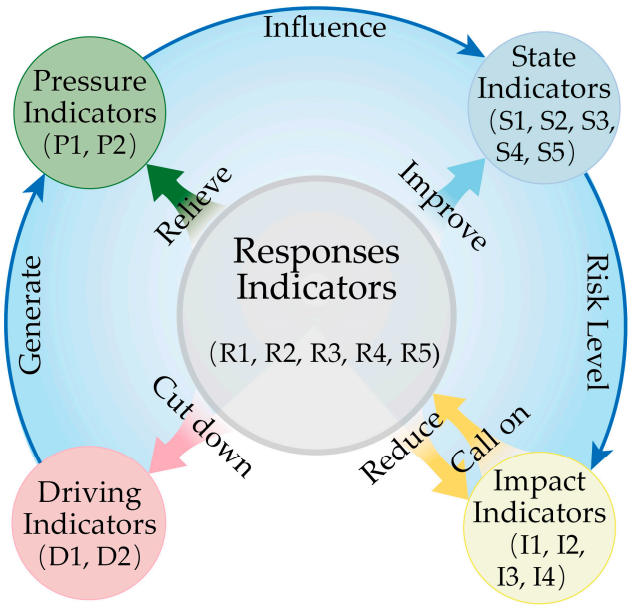


Figure 3. DPSIR framework.

To overcome the inherent limitations of these two single weighting methods, this study adopts the EW-AHP combined weighting method, balancing objectivity and subjectivity. The steps are as follows.

1. Calculation of objective weights based on the EW

a. Data standardization

To eliminate the effects of inconsistent indicator dimensions, magnitude gaps, and differences between positive and negative attributes on the scientificity of evaluation, this study adopts the min–max extremum standardization method to normalize the raw data series of all indicators, thereby converting all indicators into dimensionless standard values within the range [0, 1].

For positive indicators, Equation (1) is applied for standardization:

$$Z_{ij}^{k} = \frac{x_{ij}^{k} - x_{j,min}}{x_{j,max} - x_{j,min}} \quad (1)$$

For negative indicators, Equation (2) is used for standardization:

$$Z_{ij}^{k} = \frac{x_{j,max} - x_{ij}^{k}}{x_{j,max} - x_{j,min}} \quad (2)$$

where x_{ij}^{k} denotes the raw value of the j-th evaluation indicator for the i-th evaluated city in the k-th year; Z_{ij}^{k} denotes its standardized value; $x_{j,max} = \max_{k}\left[\max_{i}\left(x_{ij}^{k}\right)\right]$ and $x_{j,min} = \min_{k}\left[\min_{i}\left(x_{ij}^{k}\right)\right]$ denote, respectively, the maximum and minimum values of the j-th evaluation indicator across all evaluated cities and all evaluated years. $i = 1, 2, \ldots, n$ indexes the evaluated cities of Hangzhou, Ningbo, Wenzhou, Taizhou, Jinhua, Huzhou, Jiaxing, Lishui, Quzhou, Shaoxing, Zhoushan ($n = 11$ in this study). $j = 1, 2, \ldots, 18$ denotes the evaluation indicators D1, D2, P1, P2, S1, S2, S3, S4, S5, I1, I2, I3, I4, R1, R2, R3, R4, and R5, where m is the number of evaluation indicators ($m = 18$ in this paper). $k = 1, 2, \ldots, t$ denotes the evaluated years 2004, 2009, 2014, 2019, and 2024, where t is the number of

evaluated years (t = 5 in this study). The definitions of i, j, k, n, m, and t apply throughout this paper, and the same convention is used below.

b. Calculation of indicator information entropy

Based on the above dimensionless standardized values, the characteristic proportion of each evaluation indicator is calculated.

For the j-th indicator, the standardized values of all cities and all years are summed as the denominator; the characteristic proportion p_{ij}^k of the j-th indicator for the i-th city in the k-th year is calculated as follows.

Step 1: Calculate the characteristic proportion of the indicator

$$p_{ij}^k = \frac{Z_{ij}^k + \varepsilon}{\sum_{i=1}^{n} [\sum_{k=1}^{t} (Z_{ij}^k + \varepsilon)]} \tag{3}$$

where p_{ij}^k is the characteristic proportion of the j-th indicator for the i-th city in the k-th year; ε denotes a small positive constant (set to 10^{-6} in this paper), introduced to avoid an undefined value when the standardized value Z_{ij}^k is 0.

Step 2: Calculate the indicator information entropy

The information entropy of the j-th indicator is:

$$e_j = -\frac{1}{\ln(nt)} \sum_{i=1}^{n} \sum_{k=1}^{t} [p_{ij}^k \ln\left(p_{ij}^k\right)] \tag{4}$$

where $e_j \in [0, 1]$ denotes the information entropy of the j-th evaluation indicator, and p_{ij}^k denotes the characteristic proportion of the j-th evaluation indicator for the i-th city in the k-th year; n is the total number of evaluated cities (n = 11 in this study); and t is the total number of evaluated years (t = 5 in this study). The smaller the entropy value, the greater the information content of the indicator and the higher its final weight.

c. Calculation of indicator objective weights

Based on the information entropy, the objective weight is calculated.

$$w_{obj,j} = \frac{1 - e_j}{\sum_{j=1}^{m} 1 - e_j} \tag{5}$$

where $w_{obj,j}$ denotes the objective weight of the j-th evaluation indicator, with $w_{obj,j} \in [0, 1]$ and $\sum_{j=1}^{m} w_{obj,j} = 1$; e_j denotes the information entropy of the j-th indicator; and m is the total number of evaluation indicators (m = 18 in this study).

2. Calculation of subjective weights based on the AHP

a. Construction of the judgment matrix

Experts in the fields of urban and rural planning, landscape architecture, hydrology and water resources management, emergency management, and hydraulic engineering were invited. The pairwise comparison judgment matrix A^i independently constructed by the experts is:

$$\begin{cases} A^i = (a_{xy})_{m \times m} \\ x, y \in j \\ i = 1, 2, \ldots, h;\ j = 1, 2, \ldots, m \end{cases} \tag{6}$$

where a_{xy} denotes the relative importance score of the x-th indicator compared with the y-th indicator. This study adopts the 1–5 scaling method to evaluate the relative importance of the flood resilience evaluation indicators ("1/5" denotes that the x-th indicator is "very

unimportant" relative to the *y*-th; "1/3" denotes "rather unimportant"; "1" denotes "equally important"; "3" denotes "rather important"; and "5" denotes "very important"). $a_{xy} = 1$, $a_{xy} = 1/a_{yx}$; h is the number of experts; and m is the total number of evaluation indicators ($m = 18$ in this study).

The selection criteria for experts in this study were: holding a deputy senior or above professional technical title, having more than 10 years of scientific research or engineering practice experience in the relevant field, and being familiar with the actual flood control and waterlogging management situation of Zhejiang Province. The experts' professional backgrounds cover the above five disciplinary directions, including 4 university researchers and 3 senior engineers from planning and design and water conservancy management departments, totaling 7 experts.

b. Calculation of the subjective weights of indicators

The arithmetic mean method is used to solve the judgment matrices A^i of the h experts to obtain the group-decision judgment matrix $A^* = \frac{1}{h}\sum_{i=1}^{h} A^i$ ($h = 7$ in this study). MATLAB R2023b is used to solve the maximum eigenvalue λ_{max} of the matrix A^* and its corresponding eigenvector $X = (x_1, x_2, x_3, \ldots, x_m)^T$. After further normalizing X, the subjective weight of the j-th evaluation indicator is obtained:

$$w_{sub,j} = \frac{x_j}{\sum_{j=1}^{m} \mathrm{x_j}} \tag{7}$$

where $w_{sub,j}$ denotes the subjective weight of the j-th evaluation indicator, with $w_{sub,j} \in [0,1]$ and $\sum_{j=1}^{m} w_{sub,j} = 1$; x_j is the j-th component of the eigenvector corresponding to the maximum eigenvalue λ_{max} of the matrix A^*; and m is the total number of evaluation indicators ($m = 18$ in this study).

c. Consistency test of the group-decision matrix A^*

To verify the consistency of the expert scoring results and the aggregated group-decision matrix A^*, the maximum eigenvalue λ_{max} of the matrix A^* is calculated, and a standard consistency test is conducted based on the consistency index (CI) and the random consistency index (RI). The calculation formula is as follows.

$$CI = \frac{\lambda_{max} - m}{m - 1} \tag{8}$$

where λ_{max} is the maximum eigenvalue of the matrix A^*; and m is the total number of evaluation indicators ($m = 18$ in this study).

The consistency ratio (CR) is further calculated to judge the final consistency level of the matrix:

$$CR = \frac{CI}{RI} \tag{9}$$

where RI denotes the random consistency index, obtained through Monte Carlo simulation: a large number of random positive reciprocal matrices of the same order based on the 1–5 scale are generated, the mean of their maximum eigenvalues is taken, and then calculated according to Equation (8). This value is introduced to eliminate the influence of matrix dimension on the accuracy of consistency evaluation.

If the consistency ratio (CR) < 0.1, the judgment matrix is considered to have satisfactory consistency and passes the test; otherwise, the expert scoring results need to be iteratively revised and adjusted until the criterion CR < 0.1 is met.

3. Calculation of the combined weights of indicators

The subjective weights based on the AHP and the objective weights based on the EW each have advantages; the combined weight in this study is calculated as follows.

$$w_j = \alpha * w_{obj,j} + \beta * w_{sub,j} \tag{10}$$

where w_j denotes the combined weight of the j-th indicator; $w_{obj,j}$ denotes the objective weight of the j-th indicator obtained by the entropy weight method; $w_{sub,j}$ denotes the subjective weight of the j-th indicator obtained by the AHP; α denotes the importance share of the objective weight in the combined weight; and β denotes the importance share of the subjective weight in the combined weight.

Different values of α and β affect the level of the FRI; therefore, this study uses a robustness index to finally determine the importance ratio of objective and subjective weights (see Section 2.3.4 for details).

2.3.3. Calculation of the Flood Resilience Index Based on TOPSIS

This study constructs the Flood Resilience Index (FRI). TOPSIS is used to quantitatively evaluate the flood resilience level of each city in Zhejiang Province in different study years (2004, 2009, 2014, 2019, and 2024), and to analyze its spatiotemporal evolution trend.

The calculation steps of the FRI based on TOPSIS are as follows.

1. Construct the standardized evaluation matrix for the k-th year

Based on the standardized indicators Z_{ij}^k obtained from Equations (1) and (2), the standardized evaluation matrix Z^k for the k-th year is constructed:

$$Z^k = \begin{bmatrix} Z_{11}^k & \cdots & Z_{1j}^k & \cdots & Z_{1m}^k \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{i1}^k & \cdots & Z_{ij}^k & \cdots & Z_{im}^k \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{n1}^k & \cdots & Z_{nj}^k & \cdots & Z_{nm}^k \end{bmatrix} \tag{11}$$

where Z_{ij}^k is the standardized evaluation matrix for the k-th year; Z_{ij}^k is the standardized value of the j-th indicator for the i-th evaluated city in the k-th year; n is the number of evaluated cities (n = 11 in this study); and m is the total number of evaluation indicators (m = 18 in this study).

2. Construct the weighted standardized evaluation matrix for the k-th year

The combined weight w_j obtained from Equation (10) is integrated into the standardized evaluation matrix Z^k to construct the weighted standardized evaluation matrix V^k for the k-th year:

$$\begin{cases} V^k = \begin{bmatrix} V_{11}^k & \cdots & V_{1j}^k & \cdots & V_{1m}^k \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ V_{i1}^k & \cdots & V_{ij}^k & \cdots & V_{im}^k \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ V_{n1}^k & \cdots & V_{nj}^k & \cdots & V_{nm}^k \end{bmatrix} \\ V_{ij}^k = w_j Z_{ij}^k \end{cases} \tag{12}$$

where V^k is the weighted standardized evaluation matrix for the k-th year; V_{ij}^k is the weighted standardized value of the j-th indicator for the i-th city in the k-th year; w_j is the combined weight of the j-th indicator.

3. Determine the global positive and negative ideal solutions

To establish the FRI with a unified benchmark, this study constructs a global positive ideal solution (PIS) and a global negative ideal solution (NIS). The global PIS consists of the maximum value of each indicator across all evaluated cities and all evaluated years, and the global NIS consists of the minimum value of each indicator across all evaluated cities and all evaluated years. The construction process of the global PIS is as follows.

$$\begin{cases} V^+ = \left(V_1{}^+, V_2{}^+, \cdots, V_m{}^+\right) \\ V_j{}^+ = \max\limits_k \left[\max\limits_i \left(V_{ij}^k\right)\right], 1 \le i \le n, 1 \le k \le t \end{cases} \tag{13}$$

where V^+ is the global PIS; and $V_j{}^+$ denotes the maximum value of the j-th indicator across all t evaluated years and n evaluated cities (t = 5, n = 11 in this study).

Correspondingly, the construction process of the global NIS is as follows.

$$\begin{cases} V^- = \left(V_1{}^-, V_2{}^-, \cdots, V_m{}^-\right) \\ V_j{}^- = \min\limits_k \left[\min\limits_i \left(V_{ij}^k\right)\right], 1 \le i \le n, 1 \le k \le t \end{cases} \tag{14}$$

where V^- is the global NIS; and $V_j{}^-$ denotes the minimum value of the j-th indicator across all t evaluated years and n evaluated cities (t = 5, n = 11 in this study).

4. Calculate the weighted Euclidean distance of the i-th evaluated city in the k-th year to the global ideal solutions

Euclidean distance is adopted to quantify the relative closeness of the flood resilience level of the i-th city in the k-th year to the global PIS and NIS; the calculation formula is as follows.

$$\begin{cases} D_i^{k+} = \sqrt{\sum\limits_{j=1}^{m} \left(V_{ij}^k - V_j{}^+\right)^2} \\ D_i^{k-} = \sqrt{\sum\limits_{j=1}^{m} \left(V_{ij}^k - V_j{}^-\right)^2} \end{cases} \tag{15}$$

where D_i^{k+} is the Euclidean distance from the i-th evaluated city in the k-th year to the global PIS; D_i^{k-} is the Euclidean distance from the i-th evaluated city in the k-th year to the global NIS; V_{ij}^k is the weighted standardized value of the j-th indicator for the i-th city in the k-th year; and $V_j{}^+$ denotes the maximum value of the j-th indicator across all t evaluated years and n evaluated cities (t = 5, n = 11 in this study).

5. Calculate the Flood Resilience Index (FRI)

Based on the Euclidean distance calculation results, the FRI of the i-th city in the k-th year FRI_i^k is constructed:

$$FRI_i^k = \frac{D_i^{k-}}{D_i^{k-} + D_i^{k+}} \tag{16}$$

where FRI_i^k is the FRI of the i-th evaluated city in the k-th year; D_i^{k+} is the Euclidean distance to the global PIS; and D_i^{k-} is the Euclidean distance to the global NIS. A larger FRI_i^k indicates that the FRI of the i-th evaluated city in the k-th year is closer to the global PIS and farther from the global NIS, reflecting a higher flood resilience level.

6. Classification of FRI grades

The FRI grading in this study is a relative concept. The Jenks natural breaks method is used to objectively cluster the sample distribution characteristics of FRI_i^k of all t years and

n cities, and the FRI values are divided from high to low into five grades. The FRI break thresholds corresponding to each grade are shown in Table 2.

Table 2. FRI grading criteria based on the Jenks natural breaks method.

Flood Resilience Grade	FRI_i^k Interval Expression
Fifth grade	$FRI_4 < FRI_i^k \leq FRI_{\max}$
Fourth grade	$FRI_3 < FRI_i^k \leq FRI_4$
Third grade	$FRI_2 < FRI_i^k \leq FRI_3$
Second grade	$FRI_1 < FRI_i^k \leq FRI_2$
First grade	$FRI_{\min} < FRI_i^k \leq FRI_1$

The minimum value $FRI_{\min}$ among all t years and n cities is taken as the lower bound, and the 1st, 2nd, 3rd, and 4th natural breaks of FRI_1, FRI_2, FRI_3, FRI_4 are determined in turn, with the maximum value $FRI_{\max}$ among all t years and n cities as the upper bound.

2.3.4. Effect of Different Objective–Subjective Weight Importance Ratios on the FRI

The indicator weight perturbation method is adopted to analyze the influence of objective and subjective weights on the FRI. The steps are as follows.

a. Construct multiple scenarios with different objective–subjective weight importance ratios

Multiple scenarios are set for the objective and subjective weight importance ratios in Equation (10), as shown in Table 3.

Table 3. Scenarios of objective and subjective weight importance ratios.

Scenario S	Objective Weight Proportion α	Subjective Weight Proportion β
1	20%	80%
2	30%	70%
3	40%	60%
4	50%	50%
5	60%	40%
6	70%	30%
7	80%	20%

b. Calculate the FRI under different combined scenarios in turn

According to Equations (11)–(16), the FRI of the i-th evaluated city in the k-th year under scenario S $FRI_{s,i}^k$ is calculated.

c. Calculate the robustness index under different combined scenarios

To quantify the stability of flood resilience evaluation results under different combined scenarios, a robustness index is constructed as the discriminant indicator. The calculation formula is as follows.

$$Robust_s = \frac{1}{\sum_{k=1}^{t}\left(\sum_{i=1}^{n}\left|FRI_{s,i}^k - \overline{FRI_s^k}\right|\right)} \quad (17)$$

where $Robust_s$ is the robustness index under scenario s; $FRI_{s,i}^k$ is the FRI of the i-th evaluated city in the k-th year under scenario s; $\overline{FRI_s^k}$ is the mean FRI of all cities in the k-th year under

scenario s; n is the number of evaluated cities (n = 11 in this study); and t is the number of evaluated years (t = 5 in this study).

A larger index value $Robust_s$ indicates a lower spatial dispersion of the FRI evaluation results under that scenario, and a better robustness of the scheme.

d. Determination of the objective–subjective weight importance ratio

The scenario corresponding to the maximum robustness index is selected to determine the importance ratio of objective and subjective weights to the combined weight in this study. The FRI and robustness index under different objective–subjective weight ratio scenarios are detailed in Supplementary Material S4. This study finally selects an objective weight α = 80% and a subjective weight β = 20%.

2.3.5. Identification of Key Barrier Factors for Flood Resilience Improvement (BDM)

Based on the flood resilience evaluation indicator system constructed in Table 1, the standardized values Z_{ij}^k, and the combined weights w_j, the barrier degree model (BDM) is adopted to analyze the key barriers restricting the flood resilience improvement of each city in Zhejiang Province in different years. The calculation is as follows.

$$\begin{cases} O_{ij}^k = \frac{w_j D_{ij}^k}{\sum_{j=1}^m w_j D_{ij}^k} \times 100\% \\ D_{ij}^k = 1 - Z_{ij}^k \end{cases} \quad (18)$$

where O_{ij}^k denotes the barrier degree of the j-th flood resilience evaluation indicator for the i-th evaluated city in the k-th year; a larger barrier degree indicates that the factor imposes a greater constraint on flood resilience; w_j is the combined weight of the j-th indicator; D_{ij}^k denotes the indicator deviation degree, representing the gap between the j-th indicator for the i-th evaluated city in the k-th year and its ideal optimal state (value = 1); Z_{ij}^k is the standardized value of the j-th indicator for the i-th evaluated city in the k-th year; and m is the total number of evaluation indicators (m = 18 in this study). Since Equations (1) and (2) have already uniformly transformed all indicators into "the larger the value, the higher the flood resilience", the deviation degree D_{ij}^k is defined $D_{ij}^k = 1 - Z_{ij}^k$ uniformly for all indicators here, without further distinguishing between positive and negative indicators.

2.3.6. Multi-Dimensional Interaction Analysis of "Engineering–Ecological–Management"

Table 1 divides the 18 flood resilience indicators into three dimensions: engineering, ecology, and management. To further examine the coupling among the multi-dimensional factors of "engineering-ecology-management", the grey relational degree (GRD) analysis method, which is applicable to short time series and small samples, is adopted to measure the correlation strength among the dimensional indicators from 2004 to 2024.

First, according to indicator attributes, all 18 indicators are divided into the engineering dimension group (Group A), the ecological dimension group (Group B), and the management dimension group (Group C), where $A = \{Z_{ij}^k, j \in \{2, 7, 8, 9, 15, 16\}\}$, i.e., the elements of Group A consist of indicators belonging to the engineering dimension; $B = \{Z_{ij}^k, j \in \{3, 4, 5, 6, 11, 14\}\}$, i.e., the elements of Group B consist of indicators belonging to the ecological dimension; and $C = \{Z_{ij}^k, j \in \{1, 10, 12, 13, 17, 18\}\}$, i.e., the elements of Group C consist of indicators belonging to the management dimension. Here j = 1, 2, …, 18 is the indicator number, corresponding, respectively, to the indicators D1, D2, P1, P2, S1, S2, S3, S4, S5, I1, I2, I3, I4, R1, R2, R3, R4, and R5 in Table 1; i = 1, 2, …, n is the evaluated city number (n = 11 in this study); and k = 1, 2, …, t is the evaluated year number, representing 2004, 2009, 2014, 2019, and 2024 (t = 5 in this study).

To calculate the correlation among different dimensions, first the integrated sequence values of each dimension are constructed:

$$\begin{cases} A^k = \sum_{i=1}^{11}(Z_{i,2}^k + Z_{i,7}^k + Z_{i,8}^k + Z_{i,9}^k + Z_{i,15}^k + Z_{i,16}^k) \\ B^k = \sum_{i=1}^{11}(Z_{i,3}^k + Z_{i,4}^k + Z_{i,5}^k + Z_{i,6}^k + Z_{i,11}^k + Z_{i,14}^k) \\ C^k = \sum_{i=1}^{11}(Z_{i,1}^k + Z_{i,10}^k + Z_{i,12}^k + Z_{i,13}^k + Z_{i,17}^k + Z_{i,18}^k) \end{cases} \quad (19)$$

where A^k, B^k, and C^k represent the total indicator values of the engineering, ecological, and management dimensions in the k-th year, respectively; $k = 1, 2, \ldots, t$ denotes the evaluated years 2004, 2009, 2014, 2019, and 2024; and t is the total number of evaluated years ($t = 5$ in this study).

Second, the grey relational degree among different dimensions is calculated:

a. Engineering–ecology correlation γ_{AB}

$$\begin{cases} \gamma_{AB} = \frac{1}{t}\sum_{k=1}^{t}\frac{\Delta_{min}^{AB} + \zeta\cdot\Delta_{max}^{AB}}{|A^k - B^k| + \zeta\cdot\Delta_{max}^{AB}} \\ \Delta_{min}^{AB} = min_{1\le k\le t}\left|A^k - B^k\right| \\ \Delta_{max}^{AB} = max_{1\le k\le t}\left|A^k - B^k\right| \end{cases} \quad (20)$$

b. Ecology–management correlation γ_{BC}

$$\begin{cases} \gamma_{BC} = \frac{1}{t}\sum_{k=1}^{t}\frac{\Delta_{min}^{BC} + \zeta\cdot\Delta_{max}^{BC}}{|B^k - C^k| + \zeta\cdot\Delta_{max}^{BC}} \\ \Delta_{min}^{BC} = min_{1\le k\le t}\left|B^k - C^k\right| \\ \Delta_{max}^{BC} = max_{1\le k\le t}\left|B^k - C^k\right| \end{cases} \quad (21)$$

c. Engineering–management correlation γ_{AC}

$$\begin{cases} \gamma_{AC} = \frac{1}{t}\sum_{k=1}^{t}\frac{\Delta_{min}^{AC} + \zeta\cdot\Delta_{max}^{AC}}{|A^k - C^k| + \zeta\cdot\Delta_{max}^{AC}} \\ \Delta_{min}^{AC} = min_{1\le k\le t}\left|A^k - C^k\right| \\ \Delta_{max}^{AC} = max_{1\le k\le t}\left|A^k - C^k\right| \end{cases} \quad (22)$$

ζ is the distinguishing coefficient, set to the classical universal value of 0.5 in this study. t is the total number of evaluated years ($t = 5$ in this study).

2.4. Data Sources

According to the indicators in Table 1, the data sources required for this study are shown in Table 4.

Table 4. Data sources and processing methods.

Indicator	Data Source	Data Calculation Method	Missing Value Handling	Unit
D1 Permanent resident population density	Zhejiang Statistical Yearbook; statistical yearbooks of each city	Permanent resident population/Total urban area	Linear interpolation for missing years	persons/km^2
D2 Proportion of impervious area to total area	Interpretation of Landsat TM/OLI satellite remote sensing imagery (30 m × 30 m resolution)	Impervious surface area/Total urban area × 100%	Linear interpolation using adjacent-date remote sensing imagery; years without imagery estimated from the annual change rate of construction land area	%

Table 4. *Cont.*

Indicator	Data Source	Data Calculation Method	Missing Value Handling	Unit
P1 Annual frequency of heavy precipitation events (≥50 mm/h)	Hourly precipitation observations from ground meteorological stations of Zhejiang Provincial Meteorological Bureau	Count of precipitation events with hourly rainfall ≥50 mm within a year	Inverse distance weighting (IDW) spatial interpolation of nearby stations; station gaps estimated from the regression relationship between annual rainfall and heavy precipitation frequency	times/year
P2 Annual number of storm surges exceeding the warning tide level	Tide station data of the Zhejiang Marine Economic Monitoring and Early-Warning Center and the marine environment monitoring and forecasting centers of coastal cities	Number of times the measured water level at coastal tide stations exceeded the local warning tide level in that year	Linear interpolation; missing years replaced by data from adjacent coastal tide stations and verified against the number of typhoon landfalls	times/year
S1 Proportion of green space to total area	Interpretation of Landsat TM/OLI satellite remote sensing imagery (30 m × 30 m resolution)	Area of (forest land + grassland + cropland + urban park green space)/Total urban area × 100%	Linear interpolation using adjacent-date remote sensing imagery; years without data estimated from the land use transfer matrix	%
S2 Regulation and storage volume of blue-green space	Zhejiang Water Resources Bulletin; Zhejiang wetland survey bulletins; soil survey data	Reservoir capacity + adjustable storage capacity of lakes and wetlands + channel storage volume of river networks + soil water storage capacity of non-construction land	Linear interpolation; missing years estimated as the product of blue-green space area and the comprehensive per-unit-area storage coefficient	100 million m^3
S3 Compliance rate of river and seawall flood control standards	Zhejiang Provincial Department of Water Resources; annual reports of embankment project management of city water bureaus	Length of river (sea) embankments reaching the design flood (tide) control standard/Total length of river (sea) embankments × 100%	Linear interpolation; missing years use the most recent compliance inspection data, with incremental correction based on the annual length of reinforcement works	%
S4 Compliance rate of drainage pipe network design standards	Annual reports of municipal public facility construction of each city; comprehensive drainage and waterlogging prevention plans	Length of pipe networks meeting the design drainage standard (more than 1-year return period)/Total drainage pipe network length × 100%	Linear interpolation; estimated from the annual growth rate of total drainage pipe network length and the compliance proportion	%
S5 Density of flood disaster shelters	Statistical records of emergency shelters of each city emergency management bureau; primary and secondary schools and rural cultural halls available for temporary shelter	Number of qualified flood emergency shelters built (including temporary venues such as schools and public cultural halls)/Total urban area	Linear interpolation	units/km^2
I1 Proportion of the population affected by floods in the current year to total population	Statistical annual reports of flood and drought disaster prevention of the Zhejiang Provincial Department of Water Resources; post-disaster verification reports of city emergency management bureaus	Flood-affected population/Permanent resident population	Estimated from a regression model of inundated area and population density; years without disaster records set to "0" and flagged	persons per 10,000 persons
I2 Proportion of the area inundated by floods to total area	Sentinel-1 SAR remote sensing disaster monitoring; disaster reporting data of city water bureaus	Annual cumulative inundated area caused by flood/Total urban area × 100%	Estimated from the regression relationship between heavy precipitation event frequency and inundated area; or replaced by the mean of adjacent years	%

Table 4. *Cont.*

Indicator	Data Source	Data Calculation Method	Missing Value Handling	Unit
I3 Proportion of direct economic losses caused by floods to current-year GDP	Flood and drought disaster statistics of the Zhejiang Provincial Department of Water Resources; disaster verification data of city emergency management bureaus; GDP data from city statistical yearbooks	Direct economic losses caused by floods (current-year prices)/Current-year urban gross domestic product (GDP) × 100%	Estimated from a regression model of inundated area and per-unit-area asset density; years without disasters set to "0"	%
I4 Post-disaster recovery time	Post-disaster recovery assessment reports of city emergency management bureaus	Number of days from the flood disaster date to the basic return to normal production and life in the affected area	Estimated from a multiple regression on disaster severity (affected population, direct economic loss); or the mean of adjacent years	days
R1 Proportion of cumulative restored blue-green space to total area	Ecological restoration statistics of city natural resources and planning bureaus; forestry and water conservancy bureaus' afforestation and wetland restoration project records	Cumulative completed blue-green space ecological restoration area (including wetland restoration, riverbank rehabilitation, mine re-greening, etc.)/Total urban area × 100%	Linear interpolation; cumulative value estimated from the completion rate of annual ecological restoration plans	%
R2 Proportion of built sponge city area to total area	Sponge city construction records of city housing and urban–rural development bureaus	Cumulative built sponge city compliant area/Total urban area × 100%	Linear interpolation; cumulative value estimated from the annual sponge city construction plan and urban target progress	%
R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	Pumping station registration records and design documents of city water bureaus (municipal public utility management centers)	Sum of the rated design pumping and drainage flow of flood control and drainage pumping stations	Linear interpolation; total pumping capacity estimated from the annual new (renovated) pumping station plan and the average design flow of a single pump	10^3 m^3/h
R4 Establishment rate of the cross-departmental flood control and drainage linkage mechanism	Joint documents of city emergency management bureaus, water bureaus, and meteorological bureaus; revised flood emergency plans; government work reports	Cumulative number of districts/counties that have established a cross-department (emergency + water resources + methodology + natural resources + housing & construction)/Total number of districts/counties in the city × 100%	Linear interpolation; estimated from the release dates of policy documents and the progress of institutional reform	%
R5 Proportion of special flood control and drainage expenditure to total fiscal expenditure	City fiscal yearbooks; public final accounts reports	Special fiscal expenditure on flood control and drainage (including water project construction, flood emergency, etc.)/General public budget expenditure of the city × 100%	Linear interpolation; estimated from the annual growth rate of fiscal expenditure and the trend of water conservancy investment share	%

Note: In this study, the spatial resolution of the Landsat TM/OLI imagery is 30 m × 30 m, and the spatial resolution of the Sentinel-1 SAR imagery is 10 m; the radiometric calibration, atmospheric correction, image registration, land use interpretation, spatial resolution unification, and spatial analysis of all remote sensing imagery were completed on the ENVI 5.6 and ArcGIS 10.8 software platforms.

3. Results

Using the DPSIR-based flood resilience evaluation indicator system for Zhejiang Province from the EEM perspective (Table 1), through data standardization, weight calculation, global PIS and NIS solution, and FRI calculation, the flood resilience of the 11 cities in Zhejiang Province was evaluated, covering five study years: 2004, 2009, 2014, 2019, and 2024. The raw data collection process of this study is detailed in Supplementary

Material S1, the objective weight calculation process based on the entropy weight method in Supplementary Material S2, the subjective weight calculation process based on the AHP in Supplementary Material S3, and the FRI and robustness index under different objective–subjective weight ratio scenarios in Supplementary Material S4.

Table 5 presents the FRI evaluation results for the 11 cities in Zhejiang Province; Figure 3 shows the FRI grade distribution of the 11 cities; and Figure 4 shows the FRI evolution curves of the 11 cities.

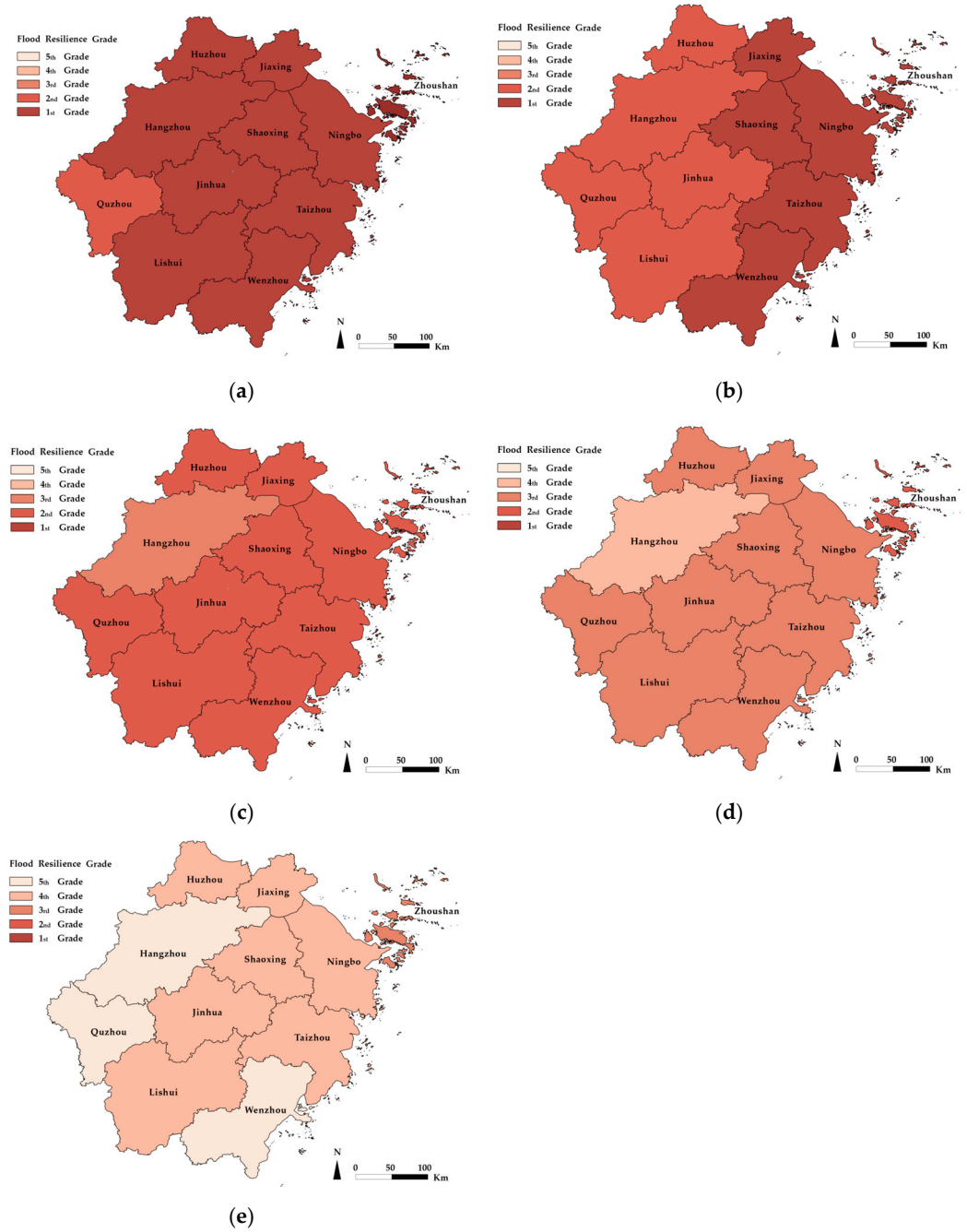


Figure 4. Spatiotemporal evolution of the FRI grade distribution of the 11 cities in Zhejiang Province (2004–2024): (**a**) 2004; (**b**) 2009; (**c**) 2014; (**d**) 2019; (**e**) 2024. Note: According to the data in Table 5 and the Jenks natural breaks method in Table 2, the 1st natural break FRI_1 in this study is 0.2087; the 2nd FRI_2 is 0.2818, the 3rd FRI_3 is 0.3850, and the 4th FRI_4 is 0.5241. The FRI range of 1st grade flood resilience is [0.1220, 0.2087], 2nd grade is (0.2087, 0.2818], 3rd grade is (0.2818, 0.3850], 4th grade is (0.3850, 0.5241], and 5th grade is (0.5241, 0.6779].

Table 5. FRI of the 11 cities in Zhejiang Province.

Region	City	2004	2009	2014	2019	2024 [Rank]	Cumulative FRI Growth Rate % (2004–2024)	Rank of Cumulative FRI Growth Rate
Northern Zhejiang	Hangzhou	0.1777	0.2356	0.3024	0.4113	0.6126 [2]	244.74	4
	Jiaxing	0.1220	0.1881	0.2782	0.3270	0.4957 [5]	306.31	1
	Huzhou	0.1906	0.2173	0.2666	0.3274	0.4626 [7]	142.71	9
	Shaoxing	0.1598	0.1986	0.2754	0.3264	0.4845 [6]	203.19	6
Eastern Zhejiang	Ningbo	0.1321	0.1938	0.2794	0.3594	0.5241 [4]	296.74	2
	Zhoushan	0.1287	0.1692	0.2469	0.2756	0.3850 [11]	199.15	7
	Taizhou	0.1249	0.1661	0.2353	0.3013	0.4626 [7]	270.38	3
Southern Zhejiang	Lishui	0.1992	0.2197	0.2634	0.3100	0.4194 [10]	110.54	11
	Wenzhou	0.1697	0.2087	0.2805	0.3701	0.5538 [3]	226.34	5
Western Zhejiang	Quzhou	0.2300	0.2525	0.2818	0.3313	0.6779 [1]	194.74	8
	Jinhua	0.1876	0.2148	0.2614	0.3279	0.4450 [9]	137.21	10
Provincial average		0.1657	0.2059	0.2701	0.3334	0.5021	203.09	—

3.1. Spatial Differentiation Characteristics of Flood Resilience

In 2024, the spatial differentiation of flood resilience in Zhejiang Province presents a hierarchical pattern of "fifth grade leading, fourth grade contiguous, and third grade dispersed", with significant regional agglomeration characteristics. As shown in Figure 4e, there are three fifth-grade flood resilience cities in 2024, namely Hangzhou (0.6126), Wenzhou (0.5538), and Quzhou (0.6779), leading the Northern, Southern, and Western Zhejiang sub-regions, respectively. The fifth-grade flood resilience cities either benefit from advantages such as a complete flood control engineering system, a solid economic foundation, and outstanding emergency management capabilities, or possess favorable natural ecological conditions. There are seven fourth grade flood resilience cities, including Ningbo (0.5241), Jiaxing (0.4957), Shaoxing (0.4845), Taizhou (0.4626), Huzhou (0.4626), Jinhua (0.4450), and Lishui (0.4194), distributed contiguously in the Northern Zhejiang Plain, the Eastern Zhejiang coast, and the central Zhejiang hilly areas. Among them, the average FRI of Northern Zhejiang (Hangzhou, Jiaxing, Huzhou, Shaoxing) in 2024 reached 0.5139, higher than the provincial average (0.5021). Only Zhoushan (0.3850) remains a third-grade flood resilience city; constrained by island geographical conditions, limited flood storage space, and inadequate coverage of engineering facilities, its FRI is only 56.8% of the provincial maximum (Quzhou, 0.6779).

The flood resilience growth rate exhibits the characteristic of "coastal plains growing faster than mountainous and island areas, with central cities leading the growth". As shown in Figure 5, in Northern Zhejiang (Figure 5a), Hangzhou consistently takes the lead, and the FRI growth rates of Jiaxing, Huzhou, and Shaoxing are close to each other; in Eastern Zhejiang (Figure 5b), after 2019 Ningbo gradually widened its gap with Zhoushan and Taizhou, while Zhoushan, constrained by geographical conditions, has a relatively low and gently growing FRI; in Southern Zhejiang (Figure 5c), the FRI gap between Lishui and Wenzhou continued to widen, with Wenzhou reaching an FRI of 0.5538 in 2024, whereas Lishui was only 0.4194; in Western Zhejiang (Figure 5d), the FRI growth rates of Quzhou and Jinhua were close from 2004 to 2019, but after 2019 Quzhou's FRI rose rapidly, reaching 0.6779 in 2024 and becoming the provincial maximum.

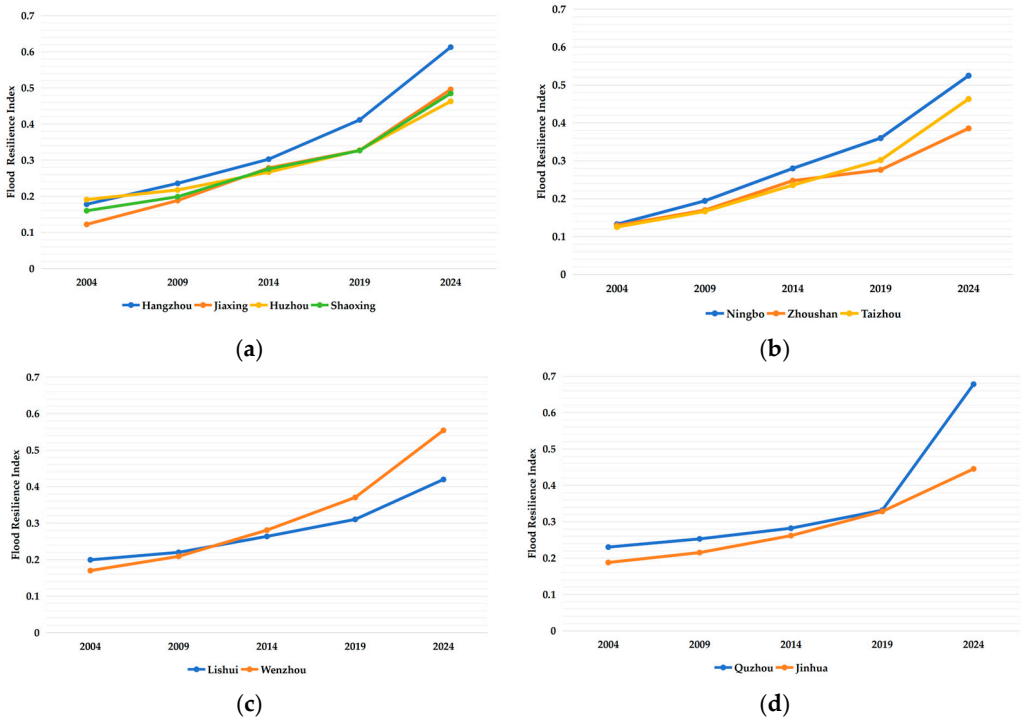


Figure 5. Interannual FRI evolution curves of Zhejiang Province: (**a**) Northern Zhejiang (Hangzhou, Jiaxing, Huzhou, Shaoxing); (**b**) Eastern Zhejiang (Ningbo, Zhoushan, Taizhou); (**c**) Southern Zhejiang (Wenzhou, Lishui); (**d**) Western Zhejiang (Jinhua, Quzhou).

3.2. Overall Evolution Characteristics of Flood Resilience

In terms of temporal differentiation, flood resilience across different cities in Zhejiang Province exhibits an evolutionary characteristic of "overall grade leapfrogging". In 2004, among the 11 cities, 10 were at Level 1 flood resilience, with only Quzhou at Level 2; in 2014, Hangzhou took the lead in entering Level 3, while the other 10 cities remained at Level 2; in 2019, Hangzhou took the lead in entering fourth grade flood resilience, the other 9 cities reached third grade, and Zhoushan remained at second grade; by 2024, three cities, Hangzhou, Wenzhou, and Quzhou, reached fifth grade flood resilience, seven cities were at fourth grade, and only Zhoushan remained at third grade.

In addition, owing to the different intensities of waterlogging measures among cities, the FRI gap among cities presents an inverted-V pattern of "from small to large and then to small", while the overall grade leaps upward. In 2004, more than 90% of the cities in the province were at a relatively low FRI level (first grade), and the provincial FRI minimum (Jiaxing, 0.1220) was 53.0% of the maximum (Quzhou, 0.2300). In 2014, the provincial FRI minimum (Taizhou, 0.2353) was 77.8% of the provincial maximum (Hangzhou, 0.3024). In 2024, the ratio of the provincial FRI minimum (Zhoushan, 0.3850) to the provincial maximum (Quzhou, 0.6779) again fell to 56.8%.

3.3. Stage Characteristics of Flood Resilience

From 2004 to 2024, the provincial average FRI exhibited a "sustained increase" characteristic, achieving a leapfrog development from "dominated by first grade" in 2004 to "dominated by fourth and fifth grade" in 2024. As shown in Table 5, the provincial average FRI rose from 0.1657 in 2004 to 0.5021 in 2024, a growth rate of 203.09%. Specifically, the growth rate was 24.26% from 2004 to 2009, with most cities at first grade flood resilience; 31.18% from 2009 to 2014, when the province entered a rapid improvement stage and 10 cities rose from first grade to second grade; 23.44% from 2014 to 2019, with 9 cities reaching third grade and Hangzhou taking the lead in entering fourth grade; and 50.60%

from 2019 to 2024, the fastest-improving of the four stages, with Hangzhou, Wenzhou, and Quzhou at fifth grade.

In terms of the FRI growth rate from 2004 to 2024 (Table 5), Jiaxing ranks first with 306.31%, followed closely by Ningbo (296.74%) and Taizhou (270.38%). Mainly affected by terrain constraints and resource limitations, Lishui (110.54%), Jinhua (137.21%), and Huzhou (142.71%) have relatively low FRI growth rates.

3.4. Flood Resilience Under Different Objective and Subjective Weight Importance Ratios Scenarios

To test the sensitivity of flood resilience evaluation results to the objective–subjective weight ratio, this study further computes the FRI of the 11 cities in Zhejiang Province for 2004, 2009, 2014, 2019, and 2024 under the seven weight-ratio scenarios presented in Table 3 of Section 2.3.4, and conducts a cross-scenario robustness test from two dimensions: city ranking and spatial pattern. The FRI values under different objective–subjective weight ratio scenarios are detailed in Supplementary Material S4.

In terms of city ranking, taking 2024 as an example (Table 6), the Spearman rank correlation coefficients of the FRI rankings of the 11 cities across the seven scenarios range from 0.891 to 1.000, with a mean of 0.966. The rank correlation between Scenario 1 and Scenario 7—which exhibit the largest weight difference—still reaches 0.891, indicating that the relative positions of cities remain largely consistent under different weight settings. At the individual-city level, Quzhou consistently ranks first across all scenarios, Hangzhou, Wenzhou, and Ningbo steadily occupy the second, third, and fourth positions, respectively, and Zhoushan remains at the bottom (11th); the head and tail of the ranking are entirely unaffected by the weight ratio. Among the middle-ranked cities, Jiaxing rises from 9th in Scenario 1 to 5th in Scenario 7 (a maximum rank shift of four positions), Lishui falls from 8th to 10th, while the rank shifts of Huzhou, Shaoxing, Taizhou, and Jinhua do not exceed two positions. Moreover, these fluctuations occur only within adjacent tiers and do not alter the flood resilience grade tier to which each city belongs.

Table 6. FRI and relative rankings of cities in Zhejiang Province under the seven scenarios in 2024.

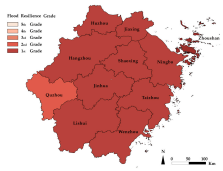
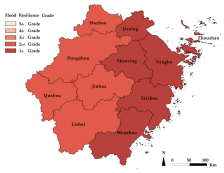
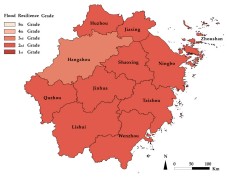
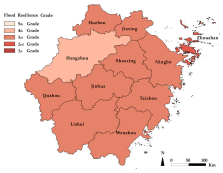
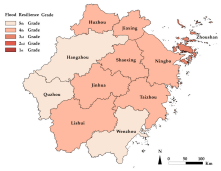
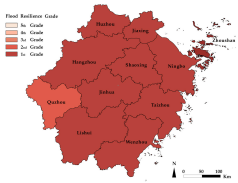
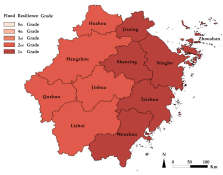
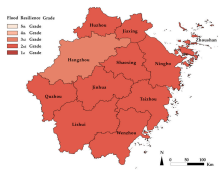
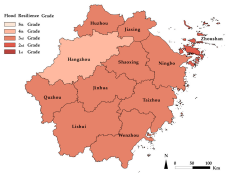
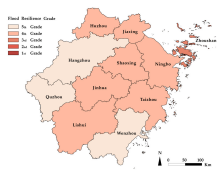
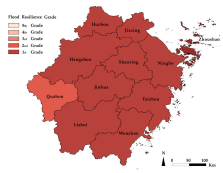
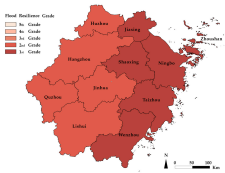
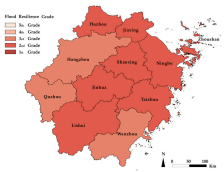
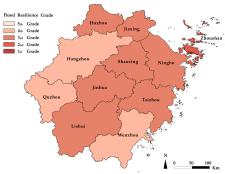
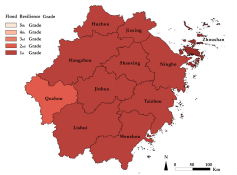
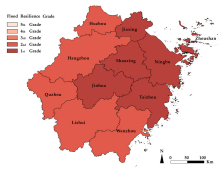
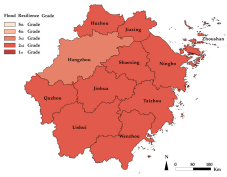
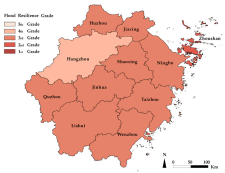
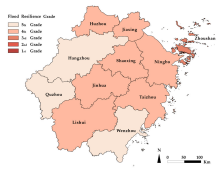
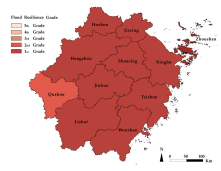
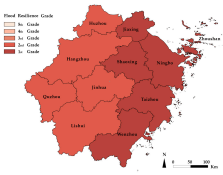
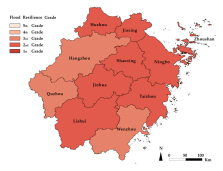
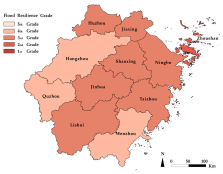
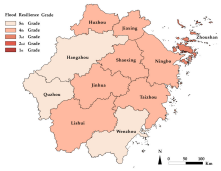
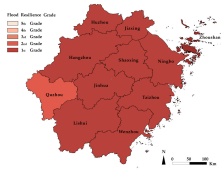
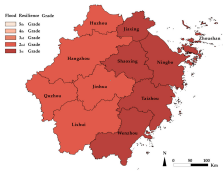
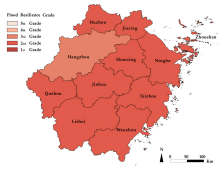
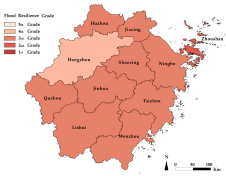
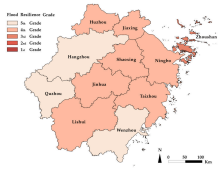
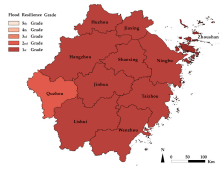
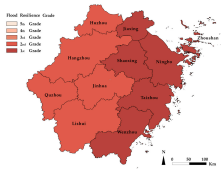
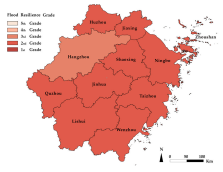
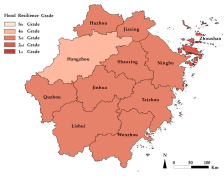
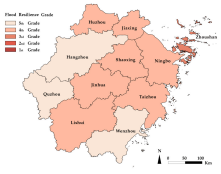
Region	City	Scenario 1 2024 [Rank]	Scenario 2 2024 [Rank]	Scenario 3 2024 [Rank]	Scenario 4 2024 [Rank]	Scenario 5 2024 [Rank]	Scenario 6 2024 [Rank]	Scenario 7 2024 [Rank]
Northern Zhejiang	Hangzhou	0.6371 [2]	0.6314 [2]	0.6263 [2]	0.6219 [2]	0.6182 [2]	0.6151 [2]	0.6126 [2]
	Jiaxing	0.5408 [9]	0.5328 [7]	0.5247 [6]	0.5167 [5]	0.5091 [5]	0.5021 [5]	0.4957 [5]
	Huzhou	0.5511 [6]	0.5338 [6]	0.5172 [7]	0.5015 [7]	0.4872 [7]	0.4742 [7]	0.4626 [7]
	Shaoxing	0.5578 [5]	0.5435 [5]	0.5297 [5]	0.5167 [5]	0.5047 [6]	0.4940 [6]	0.4845 [6]
Eastern Zhejiang	Ningbo	0.5710 [4]	0.5606 [4]	0.5511 [4]	0.5427 [4]	0.5354 [4]	0.5293 [4]	0.5241 [4]
	Zhoushan	0.4717 [11]	0.4566 [11]	0.4413 [11]	0.4261 [11]	0.4115 [11]	0.3977 [11]	0.3850 [11]
	Taizhou	0.5452 [7]	0.5283 [8]	0.5124 [8]	0.4977 [8]	0.4844 [8]	0.4727 [8]	0.4626 [8]
Southern Zhejiang	Lishui	0.5424 [8]	0.5172 [10]	0.4936 [10]	0.4719 [10]	0.4523 [10]	0.4348 [10]	0.4194 [10]
	Wenzhou	0.6271 [3]	0.6108 [3]	0.5960 [3]	0.5829 [3]	0.5716 [3]	0.5619 [3]	0.5538 [3]
Western Zhejiang	Quzhou	0.7388 [1]	0.7261 [1]	0.7143 [1]	0.7035 [1]	0.6938 [1]	0.6853 [1]	0.6779 [1]
	Jinhua	0.5386 [10]	0.5205 [9]	0.5030 [9]	0.4865 [9]	0.4712 [9]	0.4573 [9]	0.4450 [9]

In terms of spatial pattern, a comparison of the FRI spatial patterns across the seven scenarios and five years (Table 7) reveals that high-value areas are consistently concentrated in Quzhou in Western Zhejiang, the Hangzhou Bay Rim area centered on Hangzhou, and the Wenzhou region in Southern Zhejiang, whereas low-value areas persist in Zhoushan and some mountainous cities in southwestern Zhejiang. The overall spatial pattern—characterized by a gradient from southwest to northeast and a decline outward from

high-value centers over time—as well as the temporal trend of a steady year-on-year rise in provincial resilience, remain stable across all weight scenarios; no reversal of high- and low-value areas or spatial displacement attributable to weight adjustment is observed.

Neither city rankings nor the temporal evolution of the FRI spatial pattern undergoes substantive change under the seven weight assumptions. In summary, this study concludes that the research findings are insensitive to the specific ratio of objective to subjective weights, and that the results exhibit good robustness within a reasonable range of weight settings.

Table 7. Spatial pattern of FRI in Zhejiang Province across seven scenarios and five years.

Scenario S	2004	2009	2014	2019	2024
1					
2					
3					
4					
5					
6					
7					

4. Discussion

4.1. Remarkable Achievements in Flood Management

The FRI of the 11 cities in Zhejiang Province shows a trend of comprehensive improvement, which benefits from the province's sustained efforts in flood management. In terms of engineering facilities, a provincial water network has been built, forming a "three-vertical, eight-horizontal, ten-pivot" water network pattern; major flood control and drainage projects have been advanced, the Anlan Seawall Project has been implemented, and large facilities such as the Hangzhou Sanbao drainage pumping station and the upstream west-diversion project in Yuyao have been completed, markedly enhancing regional drainage capacity. Drainage pipe networks have been upgraded and city-wide sponge city construction promoted; rainwater pipe networks have been continuously newly built and renovated, pipe network desilting carried out, river regulation projects implemented, rainwater outlets cleared, and illegal structures encroaching on rivers and lakes demolished, so as to restore the natural morphology and flood conveyance capacity of watercourses. In terms of ecological restoration, blue-green space restoration and dedicated sponge city construction have been continuously advanced, and the ecological regulation and storage capacity has steadily improved. In terms of management coordination, multi-departmental collaboration among water resources, emergency management, and meteorological services has been strengthened, the share of special flood management funds in total fiscal expenditure has been raised, and the post-disaster recovery period has been shortened. Digital-enabled governance tools have been optimized, an integrated space-ground-water-engineering monitoring and sensing system has been established, and the capabilities of forecasting, early-warning, rehearsal, and pre-planning have been enhanced.

4.2. Evolution of Flood Resilience Barrier Factors

Over the 20 years from 2004 to 2024, Zhejiang Province has achieved remarkable results in flood resilience construction, but there remains a clear gap from the requirements of highly flood-resilient cities. For example, the provincial average FRI in 2024 was 0.5021, and even the top three cities by FRI, Quzhou (0.6779), Hangzhou (0.6126), and Wenzhou (0.5538), did not exceed 0.7. Faced with future flood risk, there is an urgent need to identify the key elements restricting flood resilience and to propose targeted waterlogging measures.

Applying the principle of "identification of key barrier factors for flood resilience improvement" in Section 2.3.5, Table 8 presents the top five key barrier factors and their corresponding average barrier degree values o_{ij}^{k} for each year. The identification of flood resilience barrier factors is provided in Supplementary Material S5.

As can be seen from Table 8, "R3 maximum pumping and drainage capacity of pumping stations and pipe networks" ranks first in all five observed years, and its barrier degree has continued to climb: it rose from 21.6599% in 2004 to 38.1408% in 2024, a barrier-degree growth rate of 76.1% over the two decades. This indicates that, with accelerated urbanization and increasing extreme precipitation events, the insufficient pumping and drainage capacity of pumping stations and pipe networks has consistently been the core shortage restricting the improvement of flood resilience in Zhejiang Province.

"R2 proportion of built sponge city area to total area" exhibits an inverted-V characteristic of "first rising and then falling": its barrier degree was 19.7386% in 2004, rose to 21.9430% in 2009, peaked at 24.0334% in 2014, then gradually declined to 21.4015% in 2019 and further to 16.0829% in 2024, dropping out of the top two. This trajectory is highly consistent with the advancement of sponge city construction in Zhejiang: around 2014, sponge city construction was in its initial and critical phase, and insufficient built area became a prominent barrier; as cities expanded and facilities were implemented, sponge city coverage gradually increased, and the barrier degree accordingly declined.

Table 8. Key barrier factors of provincial flood resilience in each year.

Year	Key Barrier Factor	o_{ij}^{k} (%)
2004	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	21.6599
	R2 Proportion of built sponge city area to total area	19.7386
	R1 Proportion of cumulative restored blue-green space to total area	9.8678
	R4 Establishment rate of cross-departmental flood control and drainage linkage mechanism	6.7109
	S5 Density of flood disaster shelters	7.0622
2009	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	23.8838
	R2 Proportion of built sponge city area to total area	21.9430
	R1 Proportion of cumulative restored blue-green space to total area	9.8610
	R4 Establishment rate of cross-departmental flood control and drainage linkage mechanism	7.0396
	S5 Density of flood disaster shelters	6.1862
2014	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	27.0292
	R2 Proportion of built sponge city area to total area	24.0334
	R1 Proportion of cumulative restored blue-green space to total area	9.3692
	R4 Establishment rate of cross-departmental flood control and drainage linkage mechanism	7.0205
	S5 Density of flood disaster shelters	5.3564
2019	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	29.8043
	R2 Proportion of built sponge city area to total area	21.4015
	R1 Proportion of cumulative restored blue-green space to total area	7.1938
	S5 Density of flood disaster shelters	6.7648
	P1 Annual frequency of heavy precipitation events ($\geq$50 mm/h)	6.2462
2024	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	38.1408
	R2 Proportion of built sponge city area to total area	16.0829
	S5 Density of flood disaster shelters	9.2724
	S2 Regulation and storage volume of blue-green space	7.1681
	R1 Proportion of cumulative restored blue-green space to total area	4.6814

The barrier degree of "R1 proportion of cumulative restored blue-green space to total area" shows a continuous downward trend, decreasing from 9.8678% in 2004 to 4.6814% in 2024, a decline of 52.6%, and its ranking among key barrier factors dropped from third in 2004 to fifth in 2024, reflecting that the ecological restoration of blue-green space in Zhejiang has been continuously advanced and its achievements are gradually emerging.

Management-type barrier factors present complex and variable characteristics. "R4 establishment rate of the cross-departmental flood control and drainage linkage mechanism" ranked fourth among the key barrier factors from 2004 to 2014, with its barrier degree maintained between 6.71% and 7.04%, and dropped out of the top five in 2019, indicating that the cross-departmental coordination mechanism was gradually improved in the middle period. However, "S5 density of flood disaster shelters" rose to a barrier degree of 9.2724% in 2024, jumping to third place and becoming a new shortcoming, reflecting that, as flood risk intensifies, the number and layout of existing shelters can no longer meet emergency needs.

After 2019, new changes appeared in the composition of key barrier factors: in 2019, "P1 annual frequency of heavy precipitation events ($\geq$50 mm/h)" entered the top five for the first time (barrier degree 6.2462%). In 2024, "S2: regulation and storage volume of blue-green space" entered the top five for the first time (barrier degree 7.1681), indicating

that, under climate change, intensifying extreme precipitation risk and insufficient blue-green space storage capacity are becoming new challenges facing the improvement of flood resilience in Zhejiang Province.

Combining the above evolutionary characteristics, the evolution of flood resilience barrier factors in Zhejiang Province from 2004 to 2024 can be divided into three stages:

(1) From 2004 to 2014, the province was in the stage of making up for shortcomings in engineering infrastructure: "R3 maximum pumping and drainage capacity of pumping stations and pipe networks" "R2 proportion of built sponge city area to total area" (since sponge cities had not yet been implemented in this stage, the Flood Resilience Index of all cities in Zhejiang was relatively low), and "R1 proportion of cumulative restored blue-green space to total area" constituted the top three barrier factors, with engineering-and ecology-type key barrier factors together accounting for more than 70%;

(2) From 2014 to 2019, the province was in the stage of synergistically advancing "engineering and ecology": the barrier degree of "R2 proportion of built sponge city area to total area" began to decline, "R4 establishment rate of the cross-departmental flood control and drainage linkage mechanism" dropped out of the top five, and "P1 annual frequency of heavy precipitation events (≥50 mm/h)" entered the top five, so that the composition of key barrier factors began to diversify;

(3) From 2019 to 2024, the province entered the stage of expanding engineering gaps superimposed with new barrier factors: "R3 maximum pumping and drainage capacity of pumping stations and pipe networks" rose to 38.1408%, and management- and ecology-type barrier factors such as "S5 density of flood disaster shelters" and "S2 regulation and storage volume of blue-green space" became prominent, leaving flood resilience confronted with a situation of multi-dimensional barrier factors superimposed.

4.3. Multi-Dimensional Correlation Analysis of "Engineering–Ecological–Management"

The formation and evolution of flood resilience in Zhejiang Province is the result of the interaction and dynamic coupling of the engineering, ecological, and management dimensions. Applying the multi-dimensional grey relational degree (GRD) analysis of "engineering-ecology-management" in Section 2.3.6, the relationship curves between each dimension and the observed years are shown in Figure 6 and Table 9, and the correlation degrees among the dimensions from 2004 to 2024 are shown in Table 10. The correlation analysis among the engineering, ecological, and management dimensions is detailed in Supplementary Material S5.

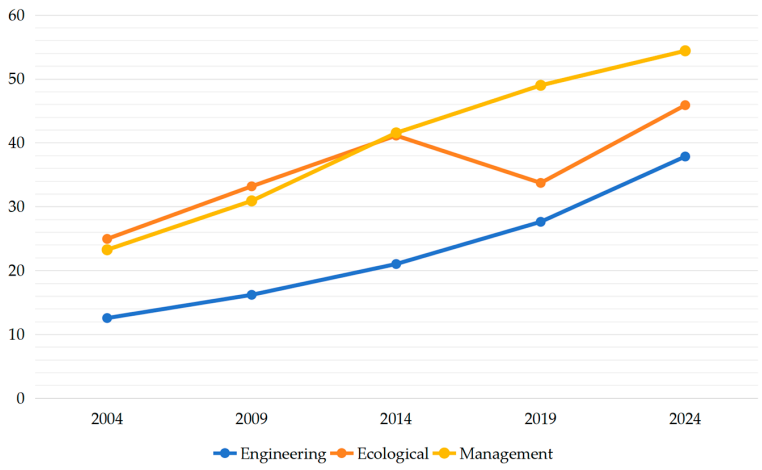


Figure 6. "Engineering–Ecological–Management" relationship curves, 2004–2024.

Table 9. Integrated sequence values of different dimensions.

Period		Value
Engineering	A^1 (2004)	12.5456
	A^2 (2009)	16.1815
	A^3 (2014)	21.0087
	A^4 (2019)	27.6144
	A^5 (2024)	37.8437
Ecological	B^1 (2004)	24.9397
	B^2 (2009)	33.1760
	B^3 (2014)	41.1227
	B^4 (2019)	33.7058
	B^5 (2024)	45.8833
Management	C^1 (2004)	23.2397
	C^2 (2009)	30.8947
	C^3 (2014)	41.5410
	C^4 (2019)	48.9906
	C^5 (2024)	54.3956

Table 10. Correlation degrees among dimensional indicators, 2004–2024.

Associated Dimensions	Correlation Degree	Correlation Strength
Engineering–Ecology	γ_{AB}	0.7488
Ecology–Management	γ_{BC}	0.7051
Engineering–Management	γ_{AC}	0.7957

4.3.1. Engineering–Ecology Correlation

The correlation degree between the engineering and ecological dimensions of flood resilience indicators is 0.7488, of medium intensity among the three correlations, reflecting that gray infrastructure and green ecological spaces are functionally complementary and advance in parallel in flood management. From 2004 to 2024, while advancing the upgrading of drainage pipe networks and the Seawall Anlan project and other engineering construction, Zhejiang continuously carried out blue-green space restoration, river regulation, and sponge city construction; the engineering and ecological measures expanded simultaneously, so the overall correlation remained at a high level. Engineering facilities undertake the core functions of rapid pumping and drainage and risk defense, while ecological spaces play the role of flood detention and peak attenuation; the two are advanced in parallel at the planning and construction level, jointly forming the spatial system of flood defense. At present, the connection between drainage pipe networks and blue-green space is insufficient, and the scale expansion of ecological space has not been effectively transformed into efficiency gains of the engineering defense system, so there remains considerable room for improving their integration.

It is worth noting that the decline of the integrated sequence value of the ecological dimension flood resilience indicators from 2014 to 2019 compared with 2009 to 2014 was not a failure of ecological governance, but rather a temporal mismatch in which "disaster pressure rose first while blue-green restoration paid off later". On the one hand, this period coincided with a strong El Niño event (2015–2016) and the intensive impact of super typhoons, and the frequency of short-duration heavy precipitation ($\geq$50 mm/h) in Zhejiang increased significantly; the number of rainstorm days in 2019 was the largest in the

corresponding period since 1961, and typhoons such as Lekima and Mitag also made the number of storm surges exceeding the warning tide level above normal. On the other hand, Zhejiang was still in the middle and late stages of rapid urbanization, with construction land continuing to expand into plain river networks and wetlands; river channel filling, canalization, and poldering weakened hydrological connectivity, whereas the "Five-Water Governance" was only fully launched in 2014 and sponge cities only entered national pilot programs in 2016, so ecological river restoration, returning polders to lakes, and wetland restoration were still under construction, and the policy dividend of cumulative blue-green restoration area had not yet been fully released. The concentration of deterioration on the pressure side and insufficient increments on the buffering side ultimately caused a phased decline in the integrated sequence value of the ecological dimension during this period; this trend rebounded after 2020 with the city-wide advancement of sponge cities and the implementation of the water security "14th Five-Year Plan".

4.3.2. Ecology–Management Correlation

From 2004 to 2024, the correlation degree between the ecological and management dimensions of flood resilience indicators is 0.7051, the lowest among the three correlations, indicating that the coordination between ecological restoration and management mechanisms still has considerable room for improvement. The flood regulation and storage effectiveness of ecological measures such as blue-green space restoration and sponge city construction depends not only on the scale of ecological space but more on the supporting management mechanisms such as cross-departmental coordinated management, spatial planning coordination, and regulation and storage volume dispatch. It is necessary, through improving management mechanisms, to incorporate the regulation and storage volume of blue-green space and the flood conveyance function into the city-wide flood management system, so as to realize the transformation of ecological restoration from "quantitative expansion" to "qualitative improvement".

4.3.3. Engineering–Management Correlation

From 2004 to 2024, the engineering–management correlation of flood resilience is 0.7957, the highest among the three pairs, reflecting the core characteristic that engineering facilities and management institutions are highly coupled in the flood management system. The flood defense effectiveness of pumping stations, embankments, and drainage pipe networks depends heavily on the support of management mechanisms such as flood dispatch, cross-departmental linkage, and emergency response; conversely, the implementation and operation of management mechanisms take the engineering system as their carrier, forming a collaborative relationship of "hardware construction-institutional safeguard". With the deepening of digital water conservancy and digital flood management, the integrated space-ground-water-engineering monitoring and sensing system has been gradually established, and the "forecast, early-warning, rehearsal, and pre-planning" capabilities have been continuously enhanced; the coordination between engineering facilities and management dispatch is further strengthened, and their correlation is shifting from a "scale-expansion type" toward an "efficiency-collaboration type".

4.4. Differentiated Flood Resilience Improvement Strategies

Based on the spatiotemporal evolution characteristics of flood resilience in Zhejiang Province (Table 5, Figures 4 and 5), the diagnosis of key barrier factors from 2004 to 2024 (Table 8), the correlation among dimensional indicators (Table 10), and the analysis of key barrier degrees for each city in 2024 (Table 11), this study further divides the 11 cities of Zhejiang into four types—Northern Zhejiang, Eastern Zhejiang, Southern Zhejiang, and

Western Zhejiang cities—according to geographical location, and proposes differentiated and targeted improvement strategies.

Table 11. Key barrier factors of flood resilience for each city in Zhejiang Province in 2024.

Region	City	Key Barrier Factor	o_{ij}^{k} (%)
Northern Zhejiang	Hangzhou	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	49.5808
		S5 Density of flood disaster shelters	13.6684
		D2 Proportion of impervious area to total area	7.2656
		S1 Proportion of green space to total area	6.5894
		P2 Annual number of storm surges exceeding the warning tide level	5.9774
	Jiaxing	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	40.5688
		R2 Proportion of built sponge city area to total area	14.6799
		S2 Regulation and storage volume of blue-green space	10.2023
		D2 Proportion of impervious area to total area	6.3436
		S1 Proportion of green space to total area	5.9912
	Huzhou	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	41.1031
		R2 Proportion of built sponge city area to total area	16.5445
		S5 Density of flood disaster shelters	8.7261
		S2 Regulation and storage volume of blue-green space	8.2431
		R1 Proportion of cumulative restored blue-green space to total area	6.5233
	Shaoxing	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	39.5904
		R2 Proportion of built sponge city area to total area	15.8485
		S2 Regulation and storage volume of blue-green space	8.8946
		S5 Density of flood disaster shelters	8.4089
		D2 Proportion of impervious area to total area	4.2153
Eastern Zhejiang	Ningbo	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	50.7335
		S2 Regulation and storage volume of blue-green space	9.3554
		S5 Density of flood disaster shelters	8.1760
		D2 Proportion of impervious area to total area	5.4645
		R2 Proportion of built sponge city area to total area	5.1567
	Zhoushan	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	34.8130
		R2 Proportion of built sponge city area to total area	21.1773
		S2 Regulation and storage volume of blue-green space	10.3540
		R1 Proportion of cumulative restored blue-green space to total area	8.5729
		P2 Annual number of storm surges exceeding the warning tide level	6.3518
	Taizhou	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	37.7012
		R2 Proportion of built sponge city area to total area	15.7229
		S5 Density of flood disaster shelters	9.2354
		S2 Regulation and storage volume of blue-green space	6.0220
		R1 Proportion of cumulative restored blue-green space to total area	4.0804

Table 11. *Cont.*

Region	City	Key Barrier Factor	o_{ij}^{k} (%)
Southern Zhejiang	Lishui	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	39.9426
		R2 Proportion of built sponge city area to total area	22.1517
		S5 Density of flood disaster shelters	11.7940
		R5 Proportion of special flood control and drainage expenditure to total fiscal expenditure	4.9679
		S2 Regulation and storage volume of blue-green space	4.5608
	Wenzhou	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	46.9452
		S5 Density of flood disaster shelters	11.1925
		R2 Proportion of built sponge city area to total area	10.3001
		P2 Annual number of storm surges exceeding the warning tide level	5.0063
		D2 Proportion of impervious area to total area	4.1058
Western Zhejiang	Quzhou	R2 Proportion of built sponge city area to total area	37.2132
		S5 Density of flood disaster shelters	18.2652
		R1 Proportion of cumulative restored blue-green space to total area	13.2033
		R5 Proportion of special flood control and drainage expenditure to total fiscal expenditure	7.9644
		R4 Establishment rate of cross-departmental flood control and drainage linkage mechanism	4.4467
	Jinhua	R3 Maximum pumping and drainage capacity of pumping stations and pipe networks	38.5700
		R2 Proportion of built sponge city area to total area	18.1167
		S5 Density of flood disaster shelters	9.8467
		S2 Regulation and storage volume of blue-green space	8.4108
		R1 Proportion of cumulative restored blue-green space to total area	5.4829

4.4.1. Northern Zhejiang Cities: Hangzhou, Shaoxing, Jiaxing, and Huzhou

The four Northern Zhejiang cities of Hangzhou, Shaoxing, Jiaxing, and Huzhou are located in the Hangzhou–Jiaxing–Huzhou Plain and the Ningbo–Shaoxing Plain, with dense river networks and a developed economy. In 2024, the average FRI of the four cities reached 0.5139, higher than the provincial average (0.5021). Among them, Hangzhou had an FRI of 0.6126, entering Level-5 flood resilience, while Jiaxing (0.4957), Shaoxing (0.4845), and Huzhou (0.4626) were all at Level 4. From 2004 to 2024, the FRI growth rate of Jiaxing was 306.31%, ranking first in the province; Hangzhou 244.74%, Shaoxing 203.19%, and Huzhou 142.71%. Figure 5a shows that the FRI growth rate of the four cities generally increased after 2019.

According to the 2024 key barrier factor diagnosis in Table 8, the four Northern Zhejiang cities present the following characteristics:

(1) "R3 maximum pumping and drainage capacity of pumping stations and pipe networks" is the common primary barrier factor for all four cities, and its barrier degree is high. The R3 barrier degree of Hangzhou is as high as 49.58%, one of the highest in the province; those of Huzhou, Jiaxing, and Shaoxing are 41.10%, 40.57%, and 39.59%, respectively, giving the four cities an average R3 barrier degree of 42.71%, significantly higher than other factors. This indicates that, as plain river-network areas, Northern Zhejiang cities generally face the pressure of "difficult outward drainage", and insufficient pumping capacity has become a bottleneck restricting flood resilience improvement.

(2) "R2 proportion of built sponge city area" is the second largest barrier factor for Jiaxing, Huzhou, and Shaoxing. The R2 barrier degree is 16.54% for Huzhou, 15.85% for

Shaoxing, and 14.68% for Jiaxing, all exceeding 14%, reflecting that Northern Zhejiang still has clear shortcomings in advancing sponge city construction and insufficient source control capacity. The second largest barrier factor of Hangzhou is "S5 density of flood disaster shelters" (13.67%), showing that, as the provincial capital and a densely populated area, Hangzhou has a more prominent supply-demand contradiction in emergency shelter space.

(3) "S2 regulation and storage volume of blue-green space" and "D2 proportion of impervious area" constitute the third tier of barrier factors. The S2 barrier degree is 10.20% for Jiaxing, 8.89% for Shaoxing, and 8.24% for Huzhou, indicating that the regulation and storage function of blue-green space has not been fully exerted; the D2 barrier degree is 7.27% for Hangzhou, 6.34% for Jiaxing, and 4.22% for Shaoxing, indicating that the impervious underlying surface of high-density built-up areas intensifies rainstorm runoff generation pressure. In addition, Hangzhou's "S1 proportion of green space to total area" (6.59%) and "P2 annual number of storm surges exceeding the warning tide level" (5.98%) also constitute certain barriers, and Huzhou's "R1 proportion of cumulative restored blue-green space to total area" (6.52%) likewise has some impact on flood resilience improvement.

In view of the above key barrier factors of Northern Zhejiang cities, the future flood resilience improvement of Hangzhou, Shaoxing, Jiaxing, and Huzhou should focus on the following four aspects:

(1) Take pumping station expansion and upgrading as the core. In response to the common problem that the R3 barrier degree of all four cities exceeds 39%, pumping station expansion and upgrading projects should be planned in advance. Hangzhou should focus on improving the pumping and drainage capacity of large pumping stations along rivers, ensuring urban drainage safety under the high backwater conditions of the Qiantang River; Jiaxing and Huzhou, in light of the long duration of high water levels in the Taihu Lake basin, should densify the layout of pumping stations in polder areas and increase single-pump power; Shaoxing, in combination with flood control dispatch in the Cao' e River basin, should optimize the operating sequence of riverside pumping stations. At the same time, the renovation of old and damaged pipe networks should be accelerated, the proportion of pipe networks operating beyond design flow should be reduced, the density of urban drainage pipe networks should be increased, and a coordinated "pumping station-pipe network" drainage system should be formed.

(2) Promote sponge city construction on a large scale. In response to the high R2 barrier degree of Huzhou (16.54%), Shaoxing (15.85%), and Jiaxing (14.68%), sponge city construction requirements should be incorporated into mandatory standards for urban renewal and new district development. The large-scale application of distributed source-control facilities such as permeable pavements, green roofs, bioretention facilities, and ecological wetlands should be expanded, with sponge facilities implemented in old residential renovation, road reconstruction and expansion, and park green space construction. Hangzhou should leverage its leading role as a national sponge city demonstration city to drive the overall quality and efficiency of sponge city construction in Northern Zhejiang.

(3) Deepen gray-green integrated management. In response to the high S2 barrier degree of Jiaxing (10.20%), Shaoxing (8.89%), and Huzhou (8.24%), the natural endowment of dense river networks in Northern Zhejiang should be fully used to construct an interconnected integrated "pipe network-river-lake" regulation and storage system. Ecological revetment renovation should be promoted, the natural regulation and storage functions of rivers, lakes, and wetlands restored and enhanced, and the

proportion of blue-green space in built-up areas increased. In response to Hangzhou's high "D2 proportion of impervious area to total area" (7.27%), the proportion of hardened ground should be reduced in urban renewal, permeable pavements and sunken green spaces promoted, and rainstorm runoff generation reduced at the source.

(4) Improve emergency shelters. In response to the prominent problem that Hangzhou's "S5 density of flood disaster shelters" barrier degree reaches 13.67%, the spatial layout of shelters should be optimized in combination with urban population distribution and disaster risk zoning, and the per capita shelter area standard should be raised. Jiaxing, Huzhou, and Shaoxing should also simultaneously promote the standardized construction of shelters, improve emergency material reserves and improve evacuation and transfer plans. Meanwhile, the leading role of Hangzhou should be brought into play to optimize the backbone water network system and its intelligent operation and dispatch, improve the cross-departmental flood control emergency linkage mechanism, and build an intelligent monitoring and dispatch system for the whole process of flood disaster management. An inter-administrative regional coordinated drainage mechanism should be established, with the Taihu Lake basin and the Cao'e River basin managed in a unified and coordinated manner, the flood regulation and storage capacity and hydrological connectivity efficiency of regional river networks improved, and the "ecology-management" coordination strengthened.

4.4.2. Eastern Zhejiang Cities: Ningbo, Taizhou, and Zhoushan

Ningbo, Zhoushan, and Taizhou are located in the Eastern Zhejiang coastal area, with interlacing bays and numerous islands, and are the core agglomeration of the marine economy and port-side industries. In 2024, the average FRI of the three cities was 0.4572, lower than the provincial average; among them, Ningbo (0.5241) and Taizhou (0.4626) were at fourth-grade flood resilience, and Zhoushan (0.3850) at third grade. From 2004 to 2024, the FRI growth rate of Ningbo was 296.74%, ranking second in the province; Taizhou 270.38%, ranking third; and Zhoushan 199.15%, ranking seventh. Eastern Zhejiang cities are areas where typhoons make landfall intensively, and the superposition of storm surges and heavy rain gives rise to high disaster risk.

According to the 2024 key barrier factor diagnosis in Table 8, the barrier structures of the three Eastern Zhejiang cities share common features but also show obvious regional differences:

(1) "R3 maximum pumping and drainage capacity of pumping stations and pipe networks" remains the primary barrier factor for all three cities, but with large internal differences. The R3 barrier degree of Ningbo is as high as 50.73%, the highest in the province, reflecting that, as a large port-side industrial and densely populated city, Ningbo has the most prominent gap in pumping and drainage capacity under extreme rainstorm conditions; the R3 barrier degree is 37.70% for Taizhou and 34.81% for Zhoushan, relatively low but still ranking first among all factors. The average R3 barrier degree of the three cities reaches 41.08%, indicating that improving flood pumping and drainage capacity is particularly important for the Eastern Zhejiang region, with its dense port-side industries and heavy rainstorm intensity.

(2) "R2 proportion of built sponge city area" is the second largest barrier factor for Zhoushan and Taizhou. The R2 barrier degree of Zhoushan is as high as 21.18%, which is closely related to its dispersed islands, tight construction land, and the difficulty of large-scale sponge facility promotion; the R2 barrier degree of Taizhou is 15.72%, also at a relatively high level. In contrast, the R2 barrier degree of Ningbo is only 5.16%, the lowest among the three cities, indicating that Ningbo has achieved good results in sponge city construction.

(3) "S2 regulation and storage volume of blue-green space" and "S5 density of flood disaster shelters" constitute secondary barriers. The S2 barrier degree is 10.35% for Zhoushan, 9.36% for Ningbo, and 6.02% for Taizhou, indicating that the stormwater regulation and storage function of blue-green space has not been fully exerted; especially for an island city such as Zhoushan, where freshwater resources are precious and storage space is limited, the multi-functional comprehensive utilization of blue-green space is particularly critical. In terms of S5, the barrier degree is 9.24% for Taizhou and 8.18% for Ningbo, with Zhoushan relatively low, reflecting that coastal cities still have problems of insufficient and unevenly distributed emergency shelter space in typhoon disasters.

(4) "P2 annual number of storm surges exceeding the warning tide level" and "R1 proportion of cumulative restored blue-green space to total area" are characteristic barrier factors of Zhoushan. The P2 barrier degree of Zhoushan is 6.35%, and the R1 barrier degree is 8.57%; these two factors occupy an important position in Zhoushan's barrier structure, reflecting that the island city faces the dual challenges of intensifying storm surge threats and insufficient ecological space restoration. The D2 barrier degree of Ningbo is 5.46%, which also requires attention in urban renewal.

In view of the above key barrier factors of Eastern Zhejiang cities, Ningbo, Taizhou, and Zhoushan should rely on their port economy and marine industry advantages to build an integrated coastal flood resilience system of "tide defense–drainage–storage", with the following key measures:

(1) Launch a pumping capacity enhancement campaign. In response to the difficult situation that the R3 barrier degree of Ningbo reaches 50.73% (the highest in the province), pumping station expansion and upgrading should be set as the flagship project for improving Ningbo's flood resilience. Combining the distribution of Ningbo's port-side industrial zones with extreme rainstorm scenarios, the layout of pumping stations should be scientifically planned, with priority given to enhancing the pumping and drainage capacity of key areas such as the Sanjiangkou core area, the Beilun port-side industrial zone, and the Hangzhou Bay New Area. Taizhou, given the heavy rainstorm intensity in the Jiaojiang River basin, should accelerate the construction and renovation of riverside pumping stations and urban drainage pumping stations; Zhoushan, in line with its island terrain, should build distributed small pumping-station clusters to improve the independent drainage capacity of individual islands.

(2) Promote sponge city construction according to local conditions. In response to the prominent problem that the R2 barrier degree of Zhoushan is as high as 21.18%, an island-characteristic sponge city construction path should be explored. In view of the dispersed islands and tight land resources of Zhoushan, permeable pavements, rain gardens, storage tanks, and other facilities should be implemented in new residential communities, public buildings, roads, and plazas, and the utilization rate of rainwater resources should be improved. Taizhou should combine new urban district development and old residential renovation to promote sponge city construction on a large scale, focusing on increasing the coverage of sponge facilities in built-up areas. Ningbo should, on the existing basis, further improve the quality and operational efficiency of sponge city construction and exert its radiating driving effect on Zhoushan and Taizhou.

(3) Strengthen the regulation and storage function of blue-green space. In response to the high S2 barrier degree of Zhoushan (10.35%) and Ningbo (9.36%), the coastal bays, rivers, and wetland resources of Eastern Zhejiang should be fully used to build a multi-scale blue-green space regulation and storage system. Zhoushan should strengthen the protection and restoration of island wetlands, build rainwater storage tanks and

ecological buffer zones, and improve the stormwater regulation and storage capacity of the islands themselves; Ningbo should, in combination with the renovation of the six banks of the three rivers, restore and enhance the regulation and storage function of riverside wetlands; Taizhou should promote the construction of ecological corridors in the Jiaojiang River basin to improve the overall basin storage capacity. Meanwhile, in response to the high R1 barrier degree of Zhoushan (8.57%), investment in island ecological restoration should be increased, and projects such as mine re-greening and shoreline ecological renovation should be promoted.

(4) Improve the coastal tide defense and emergency system. In response to the relatively high P2 barrier degree of Zhoushan (6.35%), the Seawall Anlan project should be advanced to build a combined "seawall-sluice-pumping station" tide defense system. In response to the S5 barrier degree of Taizhou (9.24%) and Ningbo (8.18%), the layout of shelters and emergency material reserves should be optimized, and the accessibility and service coverage of shelters improved. Flood-resilient construction in port-side industrial zones should be promoted, and the flood control and drainage standards and emergency response capacity of key industrial zones improved. The core driving role of Ningbo should be strengthened, the cross-departmental flood control emergency linkage mechanism improved, the flood control and drainage facilities of the Yong River, Jiaojiang River basins and the Zhoushan Archipelago coordinated, and the flood regulation and storage capacity and regional coordinated defense capacity enhanced.

4.4.3. Southern Zhejiang Cities: Wenzhou and Lishui

Lishui and Wenzhou are located at the junction of the mountainous area and the coast of Southern Zhejiang, with markedly different topography and landforms. Wenzhou is a coastal typhoon high-risk area, while Lishui is an inland mountainous city. In 2024, the average FRI of the two cities was 0.4866; among them, Wenzhou (0.5538) was at Level 5 flood resilience, and Lishui (0.4194) at Level 4. From 2004 to 2024, the FRI growth rate of Wenzhou was 226.34%, ranking fifth in the province, while that of Lishui was 110.54%, ranking last in the province, indicating a significant intra-regional gap. Figure 5c shows that the FRI gap between Wenzhou and Lishui continues to widen over time.

According to the 2024 key barrier factor diagnosis in Table 8, owing to differences in topography, landforms, and development stage, the barrier factor structure of the two Southern Zhejiang cities presents a marked "coastal-mountainous" differentiation characteristic:

(1) "R3 maximum pumping and drainage capacity of pumping stations and pipe networks" is the common primary barrier factor for both cities. The R3 barrier degree of Wenzhou is 46.95%, at a relatively high level in the province, reflecting that, as a coastal city prone to typhoon rainstorms, Wenzhou has a large gap between urban drainage pumping capacity and extreme precipitation demand; the R3 barrier degree of Lishui is 39.94%, also high, indicating that although Lishui is located in mountainous areas, insufficient pumping and drainage capacity is still the core factor restricting flood resilience improvement in river valley plains and urban built-up areas.

(2) "R2 proportion of built sponge city area to total area" is the second largest barrier factor of Lishui. The R2 barrier degree of Lishui is as high as 22.15%, which is closely related to the tight construction land, limited fiscal investment, and late start of sponge city construction in this mountainous city.

(3) "S5 density of flood disaster shelters" is a common important barrier factor for both cities. The S5 barrier degree is 11.79% for Lishui and 11.19% for Wenzhou, both exceeding 11%, significantly higher than most cities in the province. This reflects that, whether coastal or mountainous, Southern Zhejiang cities have clear shortcomings in

flood emergency shelter space: Wenzhou has frequent typhoon disasters and large shelter demand in densely populated areas; Lishui has complex mountainous terrain, making shelter layout difficult and accessibility poor.

(4) The two cities each have characteristic barrier factors, reflecting differentiated regional challenges. The R5 barrier degree of Lishui is 4.97%, and the S2 barrier degree is 4.56%, reflecting that Lishui, as a relatively underdeveloped mountainous city, faces the dual constraints of insufficient fiscal investment and under-exerted ecological storage functions. The P2 barrier degree of Wenzhou is 5.01%, and the S2 barrier degree is 10.30%, reflecting that Wenzhou, as a coastal city, faces the challenges of intensifying storm surge threats and insufficient urban blue-green space storage.

In view of the above key barrier factors of Southern Zhejiang cities, Wenzhou and Lishui should implement "coastal-mountainous" differentiated strategies, with the following key measures:

(1) Jointly advance pumping capacity construction. Wenzhou and Lishui should take pumping station expansion and upgrading as the core task of flood resilience improvement. Wenzhou should focus on the areas along the Oujiang River and the coastal plains, scientifically plan and build a number of large and medium-sized drainage pumping stations in combination with typhoon rainstorm scenarios, focusing on improving the pumping and drainage capacity of core urban areas such as Lucheng, Longwan, and Ouhai and of coastal economically strong cities such as Yueqing and Ruian. Lishui, in light of river valley plain terrain features, should focus on improving the pumping and drainage capacity of urban built-up areas such as Liandu District, while strengthening the connection between mountain flood interception ditches and downstream plain drainage pipe networks to improve mountain flood outward drainage efficiency.

(2) Lishui should prioritize making up for the shortcomings of sponge city construction. In response to the prominent problem that the R2 barrier degree of Lishui is as high as 22.15% (the highest in the province), sponge city construction should be taken as the priority area for Lishui's flood resilience improvement. Combining the characteristics of Lishui as a mountainous city, appropriate sponge city technical models should be promoted, with permeable pavements, rain gardens, and ecological detention facilities implemented in new residential communities, public buildings, and urban roads to improve the coverage of sponge facilities in built-up areas. Meanwhile, in response to the high R5 barrier degree of Lishui (4.97%), a stable growth mechanism for fiscal investment in flood management should be established, the fiscal expenditure structure optimized, and the proportion of special flood control and drainage expenditure gradually increased.

(3) Collaboratively improve the emergency shelter system. Lishui and Wenzhou should jointly promote the construction of emergency shelter space. Wenzhou, in combination with typhoon disaster risk zoning and population distribution, should focus on adding emergency shelters in coastal high-risk areas and densely populated areas, and improve the disaster resistance standards and material reserve levels of shelters. Lishui, in view of complex mountainous terrain and the difficulty of shelter layout, should adopt a layout mode combining "centralized and dispersed", building standardized shelters in townships and central villages, while using public buildings such as schools and gymnasiums to serve shelter functions, so as to improve the accessibility and service coverage of shelters.

(4) Strengthen coastal tide defense and blue-green storage. In response to the relatively high P2 barrier degree of Wenzhou (5.01%), priority should be given to the standardized construction of seawalls; the unified intelligent dispatch of reservoirs, sluices, and

pumping stations within the basin should be realized, and stormwater regulation and storage capacity should be improved. The protection and restoration of the Wenrui Plain river network and wetlands should be strengthened to enhance the storage function of blue-green space. As a mountainous city with low flood resilience, Lishui should fully leverage its mountainous ecological endowment, build systematic flood storage projects such as mountain stream ecological interception ditches, rainwater storage tanks, and ecological revetments, and improve the hydrological connectivity between the mountain flood interception system and the downstream plain drainage pipe network. Meanwhile, the radiating driving role of Wenzhou for Lishui should be brought into play, with support in technology, capital, and talent, to promote the coordinated improvement of regional flood resilience.

4.4.4. Western Zhejiang Cities: Jinhua and Quzhou

Quzhou and Jinhua are located in the Jinhua-Quzhou Basin of Western Zhejiang, with mountains, hills, and river valley plains interlaced. In 2024, the average FRI of the two cities was 0.5615; among them, the FRI of Quzhou (0.6779) was the highest in the province, at fifth-grade flood resilience, while the FRI of Jinhua was 0.4450, reaching fourth grade. From 2004 to 2024, the FRI growth rate of Quzhou was 194.74%, ranking eighth, and that of Jinhua was 137.21%, ranking tenth. Figure 5d shows that Quzhou experienced a leap after 2019, whereas Jinhua had a relatively gentle trend.

According to the 2024 key barrier factor diagnosis in Table 8, the barrier factor structures of the two Western Zhejiang cities show extremely significant internal differences:

(1) The primary barrier factors of the two cities differ. The primary barrier factor of Jinhua is "R3 maximum pumping and drainage capacity of pumping stations and pipe networks", with a barrier degree of 38.57%, consistent with most cities in the province and reflecting a clear shortcoming in engineering drainage capacity. In contrast, the primary barrier factor of Quzhou is R2, the proportion of built sponge city area, with a barrier degree as high as 37.21%. This unique phenomenon is closely related to the current status that Quzhou has the highest FRI in the province (0.6779): Quzhou is already relatively well developed in traditional water conservancy engineering, so R3 is no longer the most prominent contradiction; as flood resilience improves overall, the relative lag of ecological infrastructure such as sponge city construction has become the new primary bottleneck.

(2) "S5 density of flood disaster shelters" is the common second-largest barrier factor for both cities. The S5 barrier degree of Quzhou is as high as 18.27%, the highest in the province, reflecting that, despite its high overall flood resilience level, Quzhou has a serious shortcoming in emergency shelter space, which may be related to its complex mountainous and hilly terrain, the difficulty of shelter construction, and historical under-investment. The S5 barrier degree of Jinhua is 9.85%, also relatively high, indicating that Jinhua also needs to strengthen emergency shelter space. The average S5 barrier degree of the two cities reaches 14.06%, the highest among the four regions.

(3) Blue-green space-related factors (R1, S2) occupy an important position in obstructing the improvement of flood resilience in Quzhou. The "R1 proportion of cumulative restored blue-green space to total area" of Quzhou is 13.20%, and the "S2 regulation and storage volume of blue-green space" barrier degree is about 7.96%; the two factors together exceed 20%, reflecting that Quzhou has systemic deficiencies in the restoration and protection of blue-green space and in exerting its storage function. This somewhat contrasts with Quzhou's positioning as the ecological barrier in the upper reaches of the Qiantang River, and also shows that ecological advantages have not yet been fully

transformed into flood resilience advantages. The R1 barrier degree of Jinhua is 5.48%, and the S2 barrier degree is 8.41%, relatively low but still requiring attention.

(4) Sponge city construction is a common important barrier factor for both cities. In addition to Quzhou ranking first with an R2 barrier degree of 37.21%, the R2 barrier degree of Jinhua also reaches 18.12%, its second-largest barrier factor. The average R2 barrier degree of the two cities is as high as 27.67%, the highest among the four regions, indicating that Western Zhejiang as a whole faces the challenge of lagging sponge city construction. In addition, the R4 barrier degree of Quzhou is 4.45%, reflecting that there is also some room for improvement in management coordination.

In view of the above key barrier factors of Western Zhejiang cities, Quzhou and Jinhua should fully leverage the ecological advantages of the upper reaches of the Qiantang River, explore a flood resilience improvement path of "ecology-led, engineering shortfall compensation, and regional coordination", with the following key measures:

(1) Jinhua should prioritize making up for the engineering drainage shortfall. In response to the primary problem that the R3 barrier degree of Jinhua reaches 38.57%, pumping station expansion and upgrading and drainage pipe network construction should be taken as the priority tasks of Jinhua's flood resilience improvement. Investment in engineering construction such as pumping stations, drainage pipe networks, and embankments should be increased, and the coverage and pipe diameter standards of municipal drainage pipe networks improved. The drainage capacity along the Jinhua River and Yiwu River and in core urban areas such as Jindong and Wucheng should be improved, and old pipe network renovation and pumping station upgrades advanced simultaneously with urban renewal.

(2) Promote sponge city construction. Sponge city construction should be taken as the core lever for flood resilience improvement in Western Zhejiang. Quzhou, in view of the unique stage characteristic that R2 has become the primary barrier, should, on the basis of maintaining the advantages of traditional water conservancy engineering, shift its focus to ecological infrastructure such as sponge city construction. The sponge concept should be fully implemented in new urban district development, old residential renovation, and park green space construction, promoting permeable pavements, green roofs, bioretention facilities, and the like. Jinhua should, in combination with urban renewal and the construction of the Jinyi New Area, simultaneously advance sponge city construction and improve the coverage of sponge facilities in built-up areas. The two cities should jointly explore a Jinhua-Quzhou Basin-characteristic sponge city construction model and leverage latecomer advantages.

(3) Focus on making up the emergency shelter space shortfall. In response to the prominent problems that the S5 barrier degree of Quzhou is as high as 18.27% (the highest in the province) and that of Jinhua is 9.85%, the two cities should take emergency shelter construction as an urgent task. Quzhou, in view of complex mountainous and hilly terrain, should make full use of public buildings such as schools, gymnasiums, and exhibition centers to serve shelter functions, and improve per capita shelter area and venue accessibility. Jinhua, in combination with urban public service facility construction, should simultaneously promote the standardized renovation of shelters and improve emergency material reserves and evacuation and transfer plans.

(4) Strengthen blue-green space restoration and management coordination. In response to the high barrier degrees of ecological and management factors such as Quzhou's R1 (13.20%), S2 (7.96%), and R4 (4.45%), Quzhou should, on the basis of maintaining its leading provincial position in flood resilience, shift its work focus to ecological restoration and management coordination. Investment in blue-green space ecological restoration should be increased, and projects such as wetland protection and

restoration in the upper reaches of the Qiantang River, mine ecological treatment, and riverbank ecological renovation should be promoted, so as to increase the proportion of cumulative restored blue-green space. The river, lake, and wetland resources of the Jinhua-Quzhou Basin should be fully used to build systematic centralized flood storage projects and increase the blue-green space regulation and storage volume. The cross-departmental flood control and drainage linkage mechanism should be improved to enhance coordinated response efficiency.

5. Conclusions

Based on the DPSIR framework, this study constructs a flood resilience evaluation indicator system for Zhejiang Province from the EEM perspective, and comprehensively applies the EW-AHP combination weighting, TOPSIS, barrier degree model, and grey relational analysis methods to systematically examine the spatiotemporal evolution of flood resilience, the evolution of factors, and the cross-dimensional relationships among the 11 cities of Zhejiang Province from 2004 to 2024. The main conclusions are as follows.

(1) The flood resilience level of Zhejiang Province has improved significantly overall, but regional differentiation continues to intensify. From 2004 to 2024, the provincial average FRI rose from 0.1657 to 0.5021, a growth rate of 203.09%, and the flood resilience grade achieved a qualitative leap from "mainly first grade" to "dominated by fourth and fifth grade". In 2024, the spatial pattern of flood resilience presents a hierarchical agglomeration characteristic of "fifth grade leading, fourth grade contiguous, and third grade dispersed": Hangzhou, Wenzhou, and Quzhou enter fifth grade flood resilience, while Zhoushan, constrained by island geographical conditions, remains at third grade; the regional gap follows an inverted-V evolution of "large-small-large".

(2) The key barrier factors of flood resilience have evolved from a single engineering shortfall to a multi-dimensional composite. "R3 maximum pumping and drainage capacity of pumping stations and pipe networks" ranks as the primary barrier factor in all five study years, with its barrier degree rising from 21.66% in 2004 to 38.14% in 2024, becoming the most prominent barrier factor restricting flood resilience improvement in Zhejiang Province. The evolution of the key barrier factors is highly consistent with the different stages of flood management in Zhejiang: 2004–2014 was the stage of making up for engineering infrastructure shortfalls, 2014–2019 the stage of synergistically advancing "engineering and ecology", and 2019–2024 the stage of expanding engineering gaps superimposed with new barrier factors. In 2024, the maximum pumping and drainage capacity of pumping stations and pipe networks, the proportion of built sponge city area, the density of flood disaster shelters, the regulation and storage volume of blue-green space, and the proportion of cumulative restored blue-green space to total area became key barrier factors.

(3) The pairwise correlations among the engineering, ecological, and management factors are differentiated, and the limited integration of gray infrastructure with green space is an important factor constraining flood resilience improvement. The engineering–management correlation is the highest (0.7957), reflecting the core characteristic that engineering facilities and management institutions are highly coupled within the flood management system; the engineering-ecological correlation is intermediate (0.7488), revealing that gray engineering facilities and green ecological measures remain poorly aligned and that a truly integrated gray-green management model has yet to be established; the ecology–management correlation is the lowest (0.7051), indicating that the coordination between ecological restoration and management institutions still has considerable room for improvement.

(4) Based on regional differentiation characteristics and barrier factor diagnosis, differentiated flood resilience improvement strategies for the four regions of Northern, Eastern, Southern, and Western Zhejiang are proposed from the aspects of engineering defense, ecological restoration, and management coordination, emphasizing three directions: making up the core shortfall of pumping and drainage capacity, strengthening the "ecology-management" coordination mechanism, and promoting the gray-green integrated management model, so as to provide decision-making support for flood disaster management and flood-resilient city construction.

Although this study has achieved good results in flood resilience evaluation, barrier factor identification, and barrier factor correlation research, it still has the following limitations:

(1) Limited by indicator reliability, some indicators that can reflect flood resilience, such as the public awareness of flood risk, community self-governance and mutual assistance capacity, and flood insurance coverage, were not included in the evaluation system.
(2) This study selected five time nodes, 2004, 2009, 2014, 2019, and 2024, with an interval of 5 years. Although this covers a 20-year study period, the 5-year sampling interval may still miss short-term inter-annual fluctuations and the immediate impact and recovery process of extreme flood events on flood resilience; future work may consider collecting and analyzing year-by-year data.
(3) This study uses grey relational analysis to quantify the correlation strength among the engineering, ecological, and management factors; a high or low correlation degree only indicates the similarity of the two types of factors in temporal trends and does not fully equate to a causal transmission relationship between them. GRA reflects correlation rather than causation.
(4) In constructing the indicator system, this study incorporated regional characteristic elements of Zhejiang Province, such as the Seawall Anlan project, typhoon storm surges, city-wide sponge city construction, and the "seven parts mountain, one part water, and two parts farmland" terrain, embodying the research positioning of "regional adaptability". When this indicator framework is directly transferred to regions whose natural geographical conditions, climatic characteristics, urbanization level, and flood management model differ greatly from those of Zhejiang, some indicators may have insufficient applicability; the framework should be applied only after indicator addition or deletion, weight calibration, and framework adjustment in light of the actual characteristics of the target region.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su181910069/s1. Supplementary Material S1: Raw Data Collection Process; Supplementary Material S2: Raw Data Matrix x_{ij}^{k}, Standardized Matrix Z_{ij}^{k}, and Objective Weight Calculation Process Based on the Entropy Weight Method; Supplementary Material S3: Subjective Weight Calculation Process Based on the Analytic Hierarchy Process (AHP); Supplementary Material S4: Calculation of the Flood Resilience Index and Robustness Index under Different Objective–Subjective Weight Ratio Scenarios; Supplementary Material S5: Identification of Flood Resilience Barrier Factors and Correlation Analysis.

Author Contributions: Conceptualization, W.D.; methodology, W.D.; software, W.D.; validation, W.D.; formal analysis, W.D. and X.H.; investigation, W.D. and X.H.; resources, W.D.; data curation, W.D. and X.H.; writing—original draft preparation, W.D.; writing—review and editing, W.D.; X.H. and S.N.; visualization, W.D.; supervision, W.D.; project administration, W.D.; funding acquisition, W.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Project of Zhejiang Provincial Department of Education (Y202557647); the Project of Hangzhou Municipal Philosophy and Social Sciences (2026QTQN27); the Project of Hangzhou Agricultural and Social Development (20241029Y008); the Project of Zhejiang Provincial Department of Culture and Tourism (2025KYYY033).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the conclusions of this article can be found in Supplementary Materials S1–S5.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
BDM	Barrier Degree Model
DPSIR	Driving-Pressure-State-Impact-Response
EEM	Engineering–Ecological–Management
EW	Entropy Weight
FRI	Flood Resilience Index
GRA	Grey Relational Analysis
PIS	Positive Ideal Solution
NIS	Negative Ideal Solution
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

References

1. Ministry of Water Resources of the People's Republic of China. 2025 China Flood and Drought Disaster Prevention Bulletin. 2025. Available online: http://www.mwr.gov.cn/zzsc/tjgb/zgshzhgb/2025/mobile/index.html#p=1 (accessed on 14 August 2026).
2. Dai, W. *Spatial Planning and Design for Resilience*; A+BE Press: Delft, The Netherlands, 2021. [CrossRef]
3. Liu, D.; Wang, C.; Ji, Y.; Fu, Q.; Li, M.; Ali, S.; Li, T.; Cui, S. Measurement and analysis of regional flood disaster resilience based on a support vector regression model refined by the selfish herd optimizer with elite opposition-based learning. *J. Environ. Manag.* **2021**, *300*, 113764. [CrossRef] [PubMed]
4. Shi, C.C.; Zhu, X.P.; Wang, C.X.; Wu, F. Review and prospect of resilient cities: From the perspective of urban complex systems. *Acta Ecol. Sin.* **2023**, *4*, 1–12. (In Chinese) [CrossRef]
5. Bertilsson, L.; Wiklund, K.; de Moura Tebaldi, I.; Rezende, O.M.; Veról, A.P.; Miguez, M.G. Urban flood resilience—A multi-criteria index to integrate flood resilience into urban planning. *J. Hydrol.* **2019**, *573*, 970–982. [CrossRef]
6. Li, Z.; Zhang, X.; Ma, Y.; Feng, C.; Hajiyev, A. A multi-criteria decision making method for urban flood resilience evaluation with hybrid uncertainties. *Int. J. Disaster Risk Reduct.* **2019**, *36*, 101140. [CrossRef]
7. Rezende, O.M.; de Oliveira, A.K.B.; Jacob, A.C.P.; Miguez, M.G. A framework to introduce urban flood resilience into the design of flood control alternatives. *J. Hydrol.* **2019**, *576*, 478–493. [CrossRef]
8. Cao, F.; Xu, X.; Zhang, C.; Kong, W. Evaluation of urban flood resilience and its Space-Time Evolution: A case study of Zhejiang Province, China. *Ecol. Indic.* **2023**, *154*, 110643. [CrossRef]
9. Tang, D.; Li, J.; Zhao, Z.; Boamah, V.; Lansana, D.D. The influence of industrial structure transformation on urban resilience based on 110 prefecture-level cities in the Yangtze River. *Sustain. Cities Soc.* **2023**, *96*, 104621. [CrossRef]
10. Leal, O.J.U.; Fekete, A.; Eudave, R.R.; Matos, J.C.; Sousa, H.; Teixeira, E.R. A systematic review of integrated frameworks for resilience and sustainability assessments for critical infrastructures. *Struct. Eng. Int.* **2024**, *34*, 266–280. [CrossRef]
11. Esteban, T.A.O.; Edelenbos, J. The politics of urban flood resilience: The case of Malabon city. *Int. J. Disaster Risk Reduct.* **2023**, *88*, 103604. [CrossRef]
12. Zhu, S.; Li, D.; Feng, H.; Zhang, N. The influencing factors and mechanisms for urban flood resilience in China: From the perspective of social-economic-natural complex ecosystem. *Ecol. Indic.* **2023**, *147*, 109959. [CrossRef]
13. Zhang, R.; Li, Y.; Li, C.; Chen, T. A complex network approach to quantifying flood resilience in high-density coastal urban areas: A case study of Macau. *Int. J. Disaster Risk Reduct.* **2025**, *119*, 105335. [CrossRef]

14. Luo, Y.; Chen, X.; Yao, L. Flood disaster resilience evaluation of Chinese regions: Integrating the hesitant fuzzy linguistic term sets with prospect theory. *Nat. Hazards* **2021**, *105*, 667–690. [CrossRef]
15. Li, D.; Zhu, X.; Huang, G.; Feng, H.; Zhu, S.; Li, X. A hybrid method for evaluating the resilience of urban road traffic network under flood disaster: An example of Nanjing, China. *Environ. Sci. Pollut. Res.* **2022**, *29*, 46306–46324. [CrossRef] [PubMed]
16. Wang, P.; Li, Y.; Zhang, Y. An urban system perspective on urban flood resilience using SEM: Evidence from Nanjing city, China. *Nat. Hazards* **2021**, *109*, 2575–2599. [CrossRef]
17. Nakai, F.; Kito, S.; Okubo, K. Spatial optimisation for managed retreat and nature-based solutions in climate adaptation. *Sustain. Cities Soc.* **2025**, *124*, 106246. [CrossRef]
18. Sambowo, A.L.; Hidayatno, A. Resilience index development for the manufacturing industry based on robustness, resourcefulness, redundancy, and rapidity. *Int. J. Technol.* **2021**, *12*, 1177–1186. [CrossRef]
19. Yu, S.; Kong, X.; Wang, Q.; Yang, Z.; Peng, J. A new approach of Robustness-Resistance-Recovery (3Rs) to assessing flood resilience: A case study in Dongting Lake Basin. *Landsc. Urban Plan.* **2023**, *230*, 104605. [CrossRef]
20. Moghadas, M.; Asadzadeh, A.; Vafeidis, A.; Fekete, A.; Kötter, T. A multi-criteria approach for assessing urban flood resilience in Tehran, Iran. *Int. J. Disaster Risk Reduct.* **2019**, *35*, 101069. [CrossRef]
21. Song, J.; Chang, Z.; Li, W.; Feng, Z.; Wu, J.; Cao, Q.; Liu, J. Resilience-vulnerability balance to urban flooding: A case study in a densely populated coastal city in China. *Cities* **2019**, *95*, 102381. [CrossRef]
22. Tu, Y.; Shi, H.; Chen, K.; Liang, Y.; Zhou, X.; Lev, B. Three-reference-point based group ELECTRE III method for urban flood resilience evaluation. *Expert Syst. Appl.* **2022**, *210*, 118488. [CrossRef]
23. Jago-on, K.A.B.; Kaneko, S.; Fujikura, R.; Fujiwara, A.; Imai, T.; Matsumoto, T.; Zhang, J.; Tanikawa, H.; Tanaka, K.; Lee, B.; et al. Urbanization and subsurface environmental issues: An attempt at DPSIR model application in Asian cities. *Sci. Total Environ.* **2009**, *407*, 3089–3104. [CrossRef] [PubMed]
24. Gari, S.R.; Newton, A.; Icely, J.D. A review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. *Ocean Coast. Manag.* **2015**, *103*, 63–77. [CrossRef]
25. Tscherning, K.; Helming, K.; Krippner, B.; Sieber, S.; Paloma, S.G. Does research applying the DPSIR framework support decision making? *Land Use Policy* **2012**, *29*, 102–110. [CrossRef]
26. Huang, H.F.; Kuo, J.; Lo, S.L. Review of PSR framework and development of a DPSIR model to assess greenhouse effect in Taiwan. *Environ. Monit. Assess.* **2011**, *177*, 623–635. [CrossRef] [PubMed]
27. Lewison, R.L.; Rudd, M.A.; Al-Hayek, W.; Baldwin, C.; Beger, M.; Lieske, S.N.; Hines, E. How the DPSIR framework can be used for structuring problems and facilitating empirical research in coastal systems. *Environ. Sci. Policy* **2016**, *56*, 110–119. [CrossRef]
28. Lin, T.; Xue, X.Z.; Lu, C.Y. Analysis of coastal wetland changes using the "DPSIR" model: A case study in Xiamen, China. *Coast. Manag.* **2007**, *35*, 289–303. [CrossRef]
29. Zhang, Z.; Hu, B.; Qiu, H. Comprehensive assessment of ecological risk in southwest Guangxi-Beibu bay based on DPSIR model and OWA-GIS. *Ecol. Indic.* **2021**, *132*, 108334. [CrossRef]
30. Sobhani, P.; Esmaeilzadeh, H.; Wolf, I.D.; Deljouei, A.; Marcu, M.V.; Sadeghi, S.M.M. Evaluating the ecological security of ecotourism in protected area based on the DPSIR model. *Ecol. Indic.* **2023**, *155*, 110957. [CrossRef]
31. Chen, H.; Xu, J.; Zhang, K.; Guo, S.; Lv, X.; Mu, X.; Yang, L.; Song, Y.; Hu, X.; Ma, Y.; et al. New insights into the DPSIR model: Revealing the dynamic feedback mechanism and efficiency of ecological civilization construction in China. *J. Clean. Prod.* **2022**, *348*, 131377. [CrossRef]
32. Cui, X.Y.; Fang, L.; Wang, X.R.; Kang, J.F. Urban eco-security assessment in the urban agglomerations based on DPSIR model: A case study of Yangtze River Delta, China. *Acta Ecol. Sin.* **2021**, *41*, 302–319. (In Chinese) [CrossRef]
33. Wang, Z.; Fu, X. Scheme simulation and predictive analysis of water environment carrying capacity in Shanxi Province based on system dynamics and DPSIR model. *Ecol. Indic.* **2023**, *154*, 110862. [CrossRef]
34. Li, Y.; Liu, Y.; Yan, X. A DPSIR-based indicator system for ecological security assessment at the basin scale. *Acta Sci. Nat. Univ. Pekin.* **2012**, *48*, 971–981. (In Chinese)
35. Jiao, L.; Han, B.; Huo, X.; Zhang, Y. Research on the dynamic evolution of urban resilience in Chinese provinces based on DPSIR model and Markov Chain. *Mod. Urban Res.* **2024**, *12*, 14–20. (In Chinese)
36. Wang, Y.; Chen, H. Resilience evaluation and prediction of water supply system in Zhengzhou based on DPSIR dynamic framework. *Water Resour. Prot.* **2025**, *47*, 80–86. (In Chinese)
37. Fang, X.; Lu, L.; Li, Y.; Hong, Y. A Driver-Pressure-State-Impact-Response study for urban transport resilience under extreme rainfall-flood conditions. *Transp. Res. Part D Transp. Environ.* **2023**, *121*, 103819. [CrossRef]
38. Yuan, M.; Li, W.; Li, T.; Zhang, J. Urban Pluvial Flood Resilience Evolution and Dynamic Assessment Based on the DPSIR Model: A Case Study of Kunming City, Southwest China. *Water* **2025**, *17*, 2581. [CrossRef]

39. Karimi Sangchini, E.; Salehpour Jam, A.; Mosaffaie, J. Flood risk management in Khorramabad watershed using the DPSIR framework. *Nat. Hazards* **2022**, *114*, 3101–3121. [CrossRef]
40. Folkens, L.; Bachmann, D.; Schneider, P. Driving forces and socio-economic impacts of low-flow events in Central Europe: A literature review using DPSIR criteria. *Sustainability* **2023**, *15*, 10692. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.