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Enhancing urban flood resilience: A coupling coordinated evaluation and geographical factor analysis under SES-PSR framework

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ABSTRACT

Urban flooding has emerged as a significant urban issue in cities worldwide, with China being particularly affected. To effectively manage and mitigate urban floods, a holistic examination of the interaction between urban subsystems is required to improve urban flood resilience. However, the interactions and mechanisms between urban subsystems under flood disaster haven't been addressed adequately in previous studies. Therefore, this paper established a conceptual framework for illustrating the interactions between urban natural-ecological and social-economic subsystem considering urban pressure, state, and response within flood cycle. The objective is to investigate the coupling coordination degree (CCD) between these subsystems and identify the driving factors with a geographical detector model, and the cities in Yangtze River Delta are selected as an empirical example. The findings reveal an overall upward trend towards coordination for the whole area with notable variability among the cities. The resilience of the state dimension emerges as a crucial aspect in determining the CCD of the urban flood resilience of the area. Key driving factors for the coordinated development of urban flood resilience are identified as air pollution, global warming, technological innovation, governance power, financial strength, and urbanization. Based on the findings and the interactions among the driving factors, this paper presents potential implications that can serve as effective guidance and offer insights for policymakers, planners, and researchers in their efforts to enhance urban flood resilience for sustainable development in the future.

1. Introduction

With the advancement of urbanization, the range, intensity, and frequency of human activities have been continuously increasing, exerting a significant impact on the structure, topography, and appearance of urban systems. To some extent, these activities have also led to constantly changing climate conditions, resulting in the exacerbation of flooding disasters in many parts of the globe [1–3]. Research has shown that a 100-year flood is estimated to affect 1.81 billion people globally (23 % of the world's population). 1.24 billion of them are residents of South and East Asia, with China (395 million) and India (390 million) accounting for more than one-third of the world's affected population, and low- and middle-income nations accounting for 89 % [4]. Indeed, floods are the most common

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and devastating natural disasters of all other natural hazards, with ongoing patterns of increasing frequency, resulting in nearly 60,000 deaths in the past 50 years [5].

China, as one of the developing countries, has been significantly affected by urban flooding. This issue has emerged as a serious urban challenge alongside concerns related to population density, traffic congestion, and environmental pollution [6]. Approximately two-thirds of the country's land area is susceptible to various types and degrees of flood disasters [2]. Heavier rainfall and devasting floods have become increasingly common in China since the 1990s [7]. According to the statistics from the Ministry of Water Resources and the National Disaster Reduction Center of the Ministry of Emergency Management, China experienced an annual average of around two thousand deaths or missing people due to flood disasters from 1991 to 2020. Throughout the year of 2022, floods have harmed 33.8 million people in the country, causing a 128.9 billion yuan direct economic loss. On average, these disasters caused direct economic losses of 160.4 billion yuan per year, totaling approximately 4.81 trillion yuan [8].

To effectively address the growing threat of flooding, enhancing urban flood resilience (UFR) is a crucial strategy that requires a comprehensive understanding and assessment of a city's ability to withstand and recover from flood disasters [3,9]. UFR encompasses the capacity of urban systems to withstand, bounce back, and maintain their regular operations in the face of disruptive flood events [10]. This concept has garnered significant attention from government bodies and scholars in various disciplines, such as sociology, urban planning, disaster management, and general management. A series of global policy initiatives and commitments aimed at bolstering urban resilience have been undertaken by the United Nations, including measures specifically targeting flood resilience. Notable examples include the 2030 Agenda for Sustainable Development [11], the Sendai Framework for Disaster Risk Reduction 2015–2030 [12], and Making Cities Resilient 2030 [13]. China have also recognized the criticality of enhancing urban resilience to combat major disasters. In fact, China explicitly acknowledged this need for the first time in the "Proposal of Formulating the Fourteenth Five-Year Plan for National Economic and Social Development and the 2030 Long-Term Goals" [14].

UFR related studies mainly focused on the assessment and various indicator-based systems have been constructed to measure the resilience of urban flood hazards. Numerous studies examined UFR within the broader framework of urban resilience or utilize flooding as a case study to evaluate urban resilience [15–17]. These studies often adopt comprehensive assessment indices or metrics, such as the City Resilience Index (CRI) [18] or the Baseline Resilience Indicators for Communities (BRIC) [19], which encompass various dimensions and multi-criteria of urban resilience, including social, economic, infrastructure, community, and environmental aspects [20]. While these indices can be employed to assess UFR, they may not always provide the specificity or relevance required for a focused evaluation of flood resilience. Specific factors influencing UFR, such as flood preparedness, early warning systems, precipitation, and adaptive infrastructure, necessitate targeted metrics for a comprehensive assessment [21][10]. Some research consider UFR from the flood process perspective with simulation-based or time-sensitive model for assessing particular flood events or stages, which demand great data accuracy [22,23]. However, cities are ecosystems comprised of social, economic, and natural components. This requires holistic thinking about abilities to reflect the dynamic course of urban systems against flooding. The pressure-state-response (PSR) model has been proved to better determine the urban systems during flood cycle [10]. It provides a casual framework helping to systematically describe and analyze the interactions between society and the environment. The applicability of the PSR model in disaster management have already been explored by some scholars, such as the assessment of urban resilience with monitoring of rainstorm scenarios [24], and the flood risk assessment of urban cultural heritage in Nanjing [25].

Furthermore, as cities are a system of systems comprised of complexed subsystems [26], some studies pointed out that interactions between subdimensions may affect the quantification of urban resilience [27]. Urban areas are regarded as human-modified landscapes with numerous levels, sizes, processes, and systems because of their dynamic socio-ecological nature [28]. These areas are progressively becoming change drivers and unique ecosystem capable of creating challenges and opportunities for humankind's current and future resiliency and sustainability [29]. Research has found that cities often display clear emergent properties due to interactions among a large number of system component [30,31]. It is necessary not only to enhance understanding of the underlying principles and performance of urban flood resilience, but also to understand how to act in these processes in order to shift urban systems along more sustainable and resilient trajectories. Therefore, it is necessary to explore the interaction performance between subdimensions of urban flood resilience.

Coupling coordination degree (CCD) is used to describe the degree of harmony that exists between elements in different systems or within the same system [32]. It reflects a dynamic balance trend that progresses from disorder to order and adapts continually throughout time. As a result, it has been widely employed to investigate the coupling and coordination interactions between various systems [14]. Many studies adopted CCD to consider the interaction effects between subsystems in the context of urban urbanization, such as investigating the coupling coordination between urbanization and flood disaster [33], the coupling analysis of urbanization and energy efficiency [34], or water capacity [35]. CCD can also be used to show the performance gaps between different systems. The high CCD would be obtained only if the performance gap between the system is small [36]. However, little discussion has been emphasized on coupling coordination within the urban resilience systems and few studies adopted this point into urban flood resilience or explored the influencing factors. The complex and delicate interactions between natural resources and human activities, particularly urbanization, are called into question in order to achieve coordinated development that is adaptable to climate change and help improve urban flood resilience.

Therefore, few studies have directly measured the coupling coordination development of urban flood resilience, and the interactions and mechanisms between urban subsystems have not been addressed adequately in previous studies. To fill these research gaps, this paper aims to explore the CCD of UFR based on a conceptual framework considering both the social-economic-natural complex system and the pre-during-after flood cycle for a large region of China during a certain period. Social-ecological system (SES) model was introduced to better explain the urban subsystems and PSR model was adopted to illustrate the flood cycle. Both of them were integrated into a conceptual framework, which will be used for further influencing mechanism exploration. Then, a geographical detector model was used to investigate the driving factors affecting the CCD of UFR and provided a theoretical basis for enhancing urban flood resilience with empirical results. The works lays a scientific foundation for examining the interactions between natural, ecological, social, and economic subsystems of urban flood resilience while taking the flood disaster cycle into account. The findings can be used to generate recommendations and assist policymakers in developing more targeted and practical plans for improving urban flood resilience for sustainable development.

2. Study area

The Yangtze River, often referred to as China's mother river, has faced the constant threat of flood disasters for thousands of years. Situated at the lower reaches of the Yangtze River, the Yangtze River Delta (YRD) is an alluvial plain that has gradually formed due to the accumulation of sediments carried by the river [37]. Over the past few decades, flood disasters in the region have intensified, making it a focal point for water-related catastrophes in China. The YRD urban agglomeration, located in the eastern coastal area of China, represents a highly developed economic zone characterized by a dense population and rapid urbanization. However, due to its geographical position in a plain and low-lying area, the YRD region is particularly vulnerable to its climate, experiencing the influence of different air masses due to the demarcation line between subtropical and temperate climates [27]. Flooding in the YRD region has been exacerbated by excessive deforestation, wetland reclamation, overexpansion of riverbanks, climate change, and severe precipitation [10]. The most recent flood catastrophe in 2017 cost 1.06 billion RMB and forced 150,000 people to evacuate [38]; historically, these events have killed millions of lives, caused considerable infrastructure damage, and resulted in significant economic losses.

By acknowledging the historical significance of the Yangtze River and the persistent threat of urban floodings, we recognize the need to address the challenges faced by the YRD region. The economic prominence and rapid urbanization of the YRD urban agglomeration further emphasize the importance of implementing effective measures to mitigate flood risks and enhance resilience in this densely populated area. As shown in Fig. 1, 27 cities from three provinces (Jiangsu, Zhejiang and Anhui) and 1 municipality (Shanghai) in YRD area are chosen to contact the empirical analysis. In accordance with the beginning year of the "Development Plan for the Yangtze River Delta Urban Agglomeration", the research period spans from 2015 to 2019, excluding the impact of Covid-19 from 2020 to 2022.

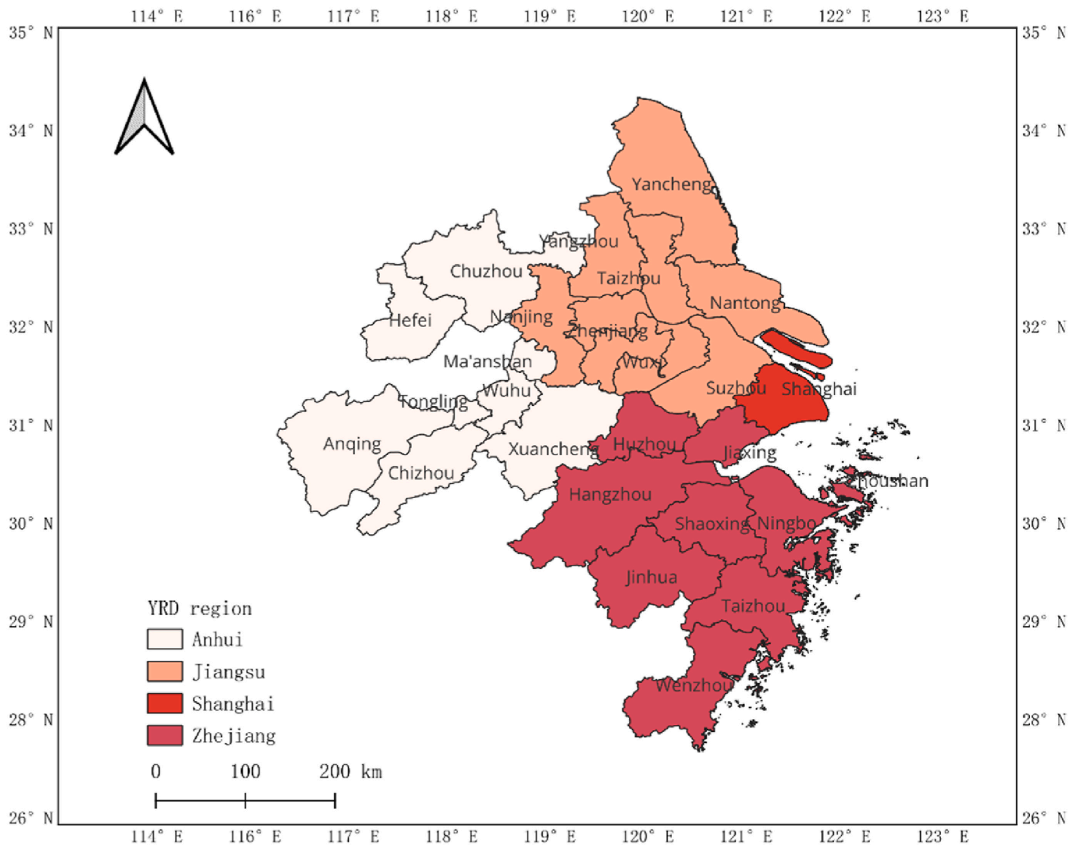

Fig. 1. Study area.

3. Methods and data

The study employs a hybrid methodology to investigate the interplay between three subdimensions of urban flood resilience and the factors that influence their interactions. The whole flowchart of the methodology is shown in Fig. 2. A conceptual framework will be built first with an establishment identified indicator systems. Next, the relationship between the subdimensions of urban flood resilience will be examined by coupling coordination model. Then, factors under the framework will be investigated by a geographical detector model to identify the driving factors and influencing mechanisms. So that possible implications for various subsystems and their interactions can be proposed.

3.1. Conceptual framework establishment

Within a social-economic-natural complex ecosystem, urban floodings are often the results of natural factors, social factors and the interaction between the two [10]. In response to the impact and interaction of human activities on the natural environment, the social-ecological systems framework (SESF) is a conceptual framework that lists a number of variables may interact and have an impact on the outcomes in social-ecological systems (SES) [39,40]. The key to the SES lies in analyzing the complexity of multi-level ecological systems across different spatial and temporal scales [40]. Ostrom believed that the social-ecological system could be divided into various subsystems. By constructing the SESF, a set of core variables and sub-variables are provided to facilitate the collection of diverse data for systematic analysis. It reexamines sustainable development issues from the perspective of the complex social-ecological system, explores the key factors that can promote sustainable resource utilization [41], and has been applied in various fields, such as urban sustainability [42], energy transition [43], and circular economy [44].

The SESF consists of two components: the social system and the ecological system (see Fig. 1), which are further divided into four core subsystems: the resource system, the resource unit, the governance system, and the actors [39]. In the context of social, economic, environmental, and political backgrounds, actors obtain resource units from the resource system and maintain the operation of the resource system based on the rules of the governance system [41,45]. Throughout this process, the social system and the ecological system are closely nested and continuously interact with each other. These four subsystems directly influence the ultimate interactive outcomes of the social-ecological system and are also influenced by the feedback from these outcomes. By introducing the SES analysis framework, it becomes possible to diagnose the complex interactive relationships within the urban social-ecological system, elucidating the hidden complex structures and interaction mechanisms in flood disaster governance and the enhancement of urban flood resilience.

Based on the SESF and PSR theory, a modified social-ecological system framework for coupling and coordination development of PSR-urban flood resilience (SES-PSR framework) was established in this paper as shown in Fig. 3. The framework encompasses the social-economic system and natural-ecological system involved in urban flood resilience. The coupling and coordination between urban flood pressure resilience, state resilience, and response resilience are the outcomes of interactions between the two systems. The di-

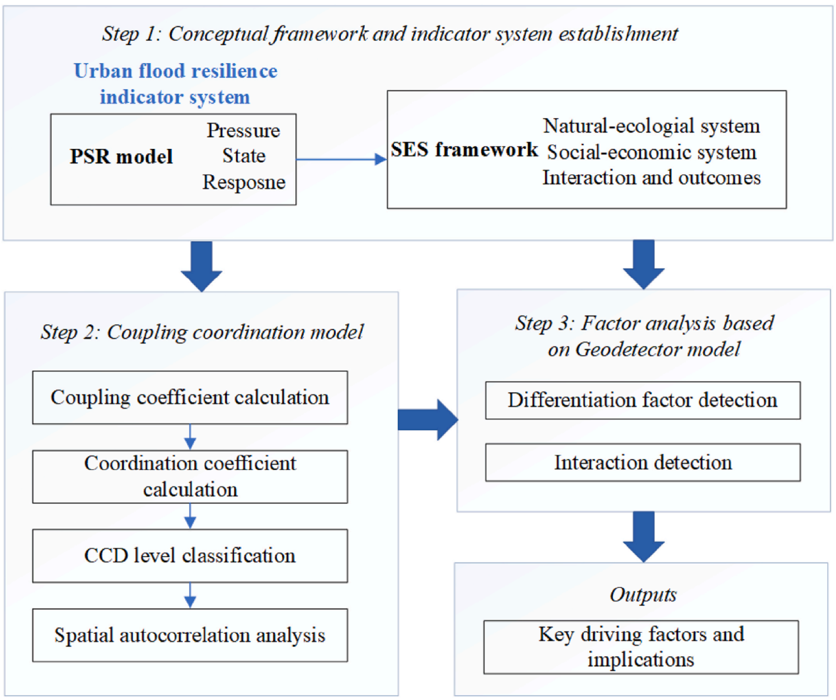

Fig. 2. Flowchart of the study.

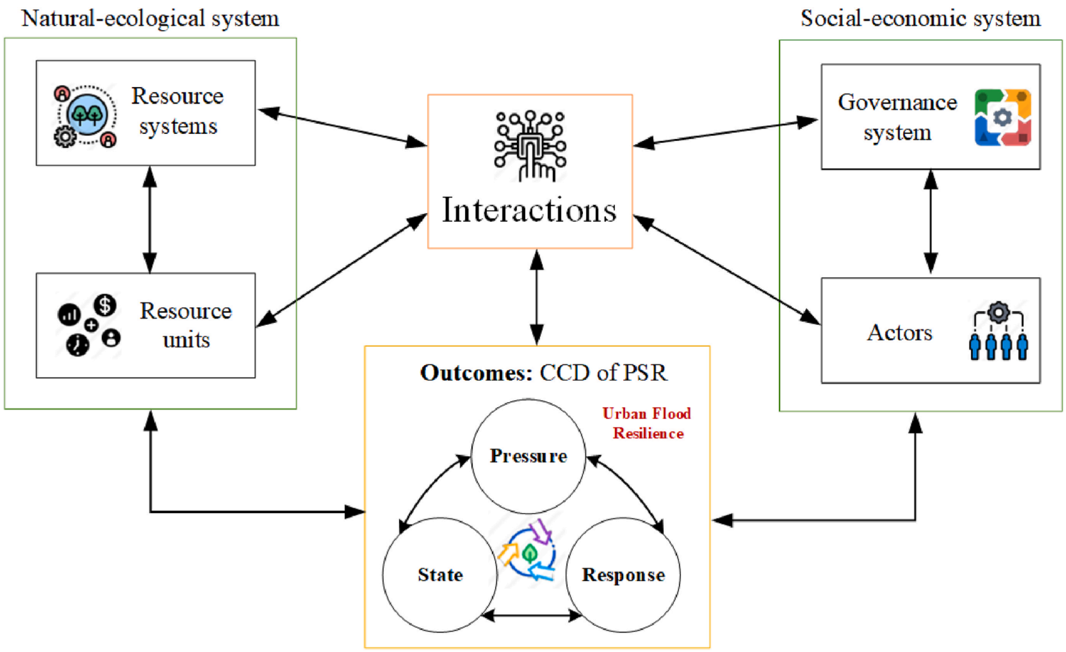

Fig. 3. SES-PSR framework.

mensions of “pressure-state-response” for urban flood resilience are formed by the combination of social, economic, and natural subsystems within the urban context.

3.2. Index system establishment

In Ostrom's SESF, each core subsystem is composed of core variables. These variables have already been defined for evaluation of resource unit, resource system, actors, governance system, interaction and outcomes [41]. Considering the concept of urban flood resilience and flood disaster cycle, modifications have been made on these variables. Justified by literatures and experts, considering the data availability, an index system based on the above SES-PSR framework was established and illustrated in Table 1.

3.2.1. Indexes in natural-ecological system

The natural-ecological system primarily includes two subsystems: the resource system and the resource unit. The core variables of the resource system mainly encompass its sector, boundaries, productivity, storage characteristics, and so on. The resource unit includes variables such as growth or replacement rate, number of units, or the spatial and temporal distribution [44]. As urban flood resilience focuses on discussing urban flood disasters, the natural-ecological system primarily considers factors related to rainfalls. Numerous scholars have proposed the existence of interactions between the atmosphere, aerosols, clouds, and rainfalls based on half a century of observations on air quality and climate change [46]. It has been demonstrated that the concentration and properties of aerosols in air pollution sources significantly influence the formation of precipitation [47]. Temperature variations also have an impact on rainfall. Through the analysis of the spatiotemporal changes in extreme climate elements in China and Australia, researchers

Table 1
Influence factors of coupling and coordination effect of urban flood resilience.

SESF	Sub-dimension	Index	Justification
Natural-ecological system (Resource systems and units)	Air pollution	X1: Emissions of industrial pollutants (such as sulfur dioxide, smoke and dust)	[46,47]
	Global warming	X2: Monthly average maximum temperature	[48]
Social-economic system (Governance system and Actors)	Technological innovation	X3: Patents granted number	[49,50]
	Governance power	X4: Public finance expenditure ratio	[21,51]
	Financial strength	X5: City deposit balance	[10,27]
	Number of relevant actors	X6: Citizen growing rate	[52]
	Stakeholders	X7: Proportion of practitioners in water conservancy, environment and public facilities management to total employees	[10,17]
Interaction	Urbanization	X8: Urbanization ratio (population)	[15,16,53]
		X9: Built-up area ratio (land)	
		X10: Total retail sales of social consumer goods per capita (economy)	
outcomes	P–S-R coupling and coordination results	P–S-R urban flood resilience system	[54]

have proven that the increase in extreme high temperatures leads to more frequent extreme rainfall events [48] [55]. Climate change, by affecting the precipitation process, poses significant challenges to the sustainable development and utilization of global and regional water resources. Extreme rainfall is the most direct driving factor of urban flooding events, and climate change directly contributes to global changes in rainfall patterns [48,56,57]. Therefore, in terms of the natural-ecological system, air pollution and climate change, especially temperature change are considered as the two main influencing factors. X1: Emissions of industrial pollutants (such as sulfur dioxide, smoke and dust) and X2: Monthly average maximum temperature are used to demonstrate these two factors.

3.2.2. Indexes in social-economic system

The socio-economic system comprises two subsystems: the governance system and the actors. The core variables of the governance system include management organizations, operational rules, and operational regulations. The actors primarily encompass the number of users, economic attributes, government leadership, and knowledge reserves [44]. Scholars have investigated the factors influencing urban resilience and found that government administrative spending, market forces, openness, and innovation all have varied degrees of direct or indirect influence on urban resilience [17,21]. Government factors, market factors, technological factors, financial factors, and others have an overall positive impact on urban resilience [51]. In this dimension, factors such as changes in the number of urban residents (X6), the number of managers responsible for public facilities such as water resources (X7), government administrative capacity (X4), financial capacity (X5), and technological innovation capability (X3) are selected as influencing factors for the coupling and coordination of PSR-urban flood resilience.

3.2.3. Indexes for interaction

In SES-PSR framework, the interactions between the natural-ecological system and the socio-economic system directly impact the final outcomes. The main variables include actor activities, conflicts, contradictions, and so on [45], which are primarily manifested as the interaction between humans and nature for urban flood resilience. Numerous studies have shown that urbanization increases urban rainfall, and as the process of urbanization speeds, so does the probability of intense rainfall events, heightening the risk of urban flood disasters [21,58], [57]. Some research also proved that there is a certain level of coupling and coordination between urban resilience and the level of urbanization [53]. As the degree of coupling grows, it promotes greater coordination, resulting in a narrowing of the gap between urban resilience and urbanization level [59]. Therefore, in terms of the interaction between the two systems, variables such as population (X8), land (X9), and the level of urbanization in the economy (X10) are selected as influencing factors for the coupling and coordination of PSR-urban flood resilience.

3.2.4. Indexes for outcomes-PSR coupling and coordination

The coupling and coordination of PSR in urban flood resilience refers to the interdependence, interaction, and mutual constraint of resilience in pressure, state, and response dimensions in the face of flood disasters. It entails a gradual transition from disorder to order in a constantly changing process, ultimately forming a virtuous cycle characterized by mutual coordination, interaction, and harmonious coherence. The indexes for PSR urban resilience are revised from flood resilience evaluation related research [58], [54], [10], in which the indexes are considered from dimensions including natural pressure, natural state, social state, economic state, natural response, social response and economic response. Detailed indexes can be found in Fig. 4 and Table A1.

3.3. Coupling coordination model

3.3.1. The coupling coefficient calculation

The coupling coefficient of multiple systems generally adopts the following model [27]:

$$C_n = \left\{ \frac{(u_1 \times u_2 \ldots \times u_n)}{\prod (u_i + u_j)} \right\}^{\frac{1}{n}} \tag{1}$$

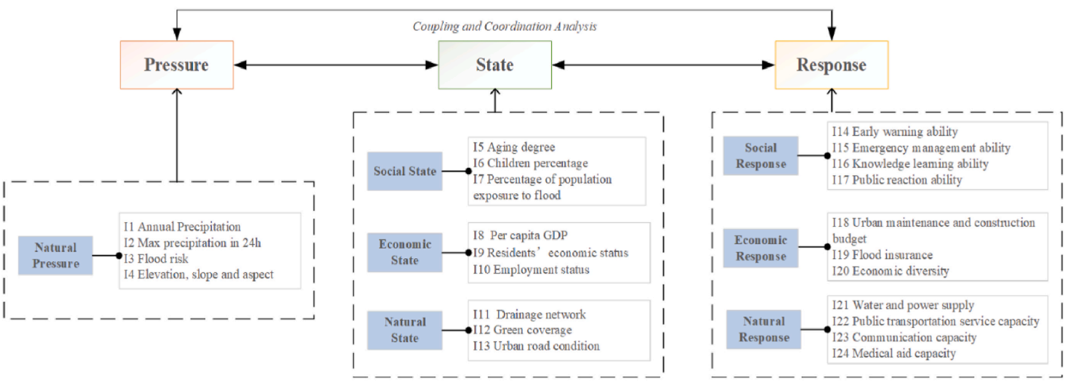

Fig. 4. Indexes for P–S-R urban flood resilience.

Where the coupling coefficient, represented by C_n indicates the level of coupling between different systems. A higher value of C signifies a higher degree of coupling among the systems. When C equals 1, it represents the maximum level of coupling, indicating a state of beneficial resonance coupling. On the other hand, when C equals 0, it represents the minimum level of coupling, indicating the absence of interaction among the subsystems and a state of unrelated and disordered development. $\prod(u_i + u_j)$ means find the product of $u_i + u_j$, where i and j = 1,2,3, …n.

In this paper, C represents the coupling coefficient of urban flood resilience, and u represents the urban flood resilience, which is measured by Entropy wight-VIKOR model. All indicators are standardized and the final flood resilience for all cities ranges from 0 to 1. The detailed procedure of the method can be found in our previous research [60]. In equation (2), U_{Pre} represents the flood resilience for pressure dimension, U_{Sta} represents the flood resilience for state dimension, and U_{Res} represents the flood resilience for response dimension. Therefore, the internal coupling coefficient of urban flood resilience can be calculated using the following formula:

$$C_R = \left\{ \frac{(U_{Pre} \times U_{Sta} \times U_{Res})}{(U_{Pre} + U_{Sta} + U_{Res})^3} \right\}^{\frac{1}{3}} \tag{2}$$

The calculation of the coupling coefficient for pressure-state resilience is as follows:

$$C_{p-s} = \left\{ \frac{(U_{Pre} \times U_{Sta})}{(U_{Pre} + U_{Sta})^2} \right\}^{\frac{1}{2}} \tag{3}$$

The calculation of the coupling coefficient for pressure-response resilience is:

$$C_{p-r} = \left\{ \frac{(U_{Pre} \times U_{Res})}{(U_{Pre} + U_{Res})^2} \right\}^{\frac{1}{2}} \tag{4}$$

The calculation of the coupling coefficient for state-response resilience is:

$$C_{s-r} = \left\{ \frac{(U_{Sta} \times U_{Res})}{(U_{Sta} + U_{Res})^2} \right\}^{\frac{1}{2}} \tag{5}$$

3.3.2. The coordination coefficient calculation

The coupling coefficient can only reflect the mutual influence and interaction among the dimensions of urban flood resilience but cannot reflect the comprehensive development level of urban flood resilience [53]. It is possible to have a high degree of coordination but a low overall development level. Therefore, based on the results of the coupling coefficient, it is necessary to further construct a coupling coordination model to assess the coupling coordination status of urban flood resilience. The specific formula is as follows:

$$D_R = \sqrt{C_R \times T_R} \tag{6}$$

where, D_R represents the CCD for urban flood resilience, C_R represents the coupling coefficient, and T_R represents the development level for urban flood resilience, which can be calculated by equation (7).

$$T_R = \alpha U_{Pre} + \beta U_{Sta} + \gamma U_{Res} \tag{7}$$

Where α , β , γ are the undetermined coefficients, and $\alpha + \beta + \gamma = 1$. Since the urban flood resilience in pressure is as important as it in state and response dimensions, the value is selected as $\alpha = \beta = \gamma = 1/3$. Accordingly, in the calculations of the coupling coordination degree for pressure-state (T_{p-s}), pressure-response (T_{p-r}), and state-response (T_{p-s}), the coefficient is set to 1/2. The formula for the development degree is as follows:

$$T_{p-s} = 0.5U_{Pre} + 0.5U_{Sta} \tag{8}$$

$$T_{p-r} = 0.5U_{Pre} + 0.5U_{Res} \tag{9}$$

$$T_{p-s} = 0.5U_{Sta} + 0.5U_{Res} \tag{10}$$

3.3.3. CCD level classification and spatial autocorrelation analysis

The CCD of UFR is determined by both the coupling coefficient and the development level. To clearly reflect the coupling coordination level between pressure, state, and response dimensions, the classification of CCD for urban flood resilience is based on the division criteria from relevant studies [27,53]. The specific classifications are shown in Table 2.

Based on the above classification, the spatial distribution characteristics of UFR was explored through the global Moran's I index [61]. The calculated global Moran's I index ranges from −1 to 1. The range [−1, 0) indicates negative spatial correlation, I = 0 indi-

Table 2
Measurement standard of CCD for PSR urban flood resilience.

CCD level	CCD type
[0.00,0.20)	Extreme imbalance
[0.20,0.30)	Moderate imbalance
[0.30,0.40)	Low imbalance
[0.40,0.50)	Primary coordination
[0.50,0.70)	Moderate coordination
[0.70, 1.00]	Excellent coordination

cates no spatial autocorrelation, and (0, 1] indicates positive spatial correlation [62]. The significance test for the global Moran's I index typically uses a two-tailed test, and the test statistic is represented by the Z statistic:

$$Z = \frac{I - E(I)}{\sqrt{Var(I)}} \tag{11}$$

where I represents the observed Moran's I index. E(I) represents the expected Moran's I index under the null hypothesis of no spatial autocorrelation. Var(I) represents the variance of the Moran's I index. When the Moran's I index is both significant and positive, it indicates a significant positive correlation, suggesting that similar observations of UFR values (high or low values) tend to be spatially clustered. Conversely, when the Moran's I index is both significant and negative, it indicates a significant negative correlation, suggesting that similar observations of UFR values tend to be dispersed.

3.4. Factor analysis based on geodetector model

Based on the SES-PSR framework, the coupled and coordinated development in the dimensions of pressure, state, and response is the result of the interaction between the socio-economic system and the natural-ecological system. Therefore, it is necessary to explore the effects of various external influencing factors on the CCD of urban flood resilience from three aspects including socio-economic, natural-ecological, and interactive. Due to the different spatial manifestations in the research area in terms of society, economy, nature, and other aspects, it is necessary to detect the effects of various driving factors from a spatial differentiation perspective.

Geodetector, proposed by Professor Wang Jinfeng and others in 2010, is a new statistical method for detecting spatial differentiation and revealing the underlying driving factors [63]. The essential principle is as follows: assuming that the research area is separated into numerous sub-regions, there is spatial differentiation if the sum of variances of the sub-regions is less than the overall variance of the region. If the spatial distributions of two variables tend to be consistent, there is statistical correlation between them [64]. Compared with traditional statistical methods, the Geodetector model does not require linear assumptions during analysis, only appropriate discretization is needed. The main advantage of this method is that it is free of assumptions and constraints, and it is universal, effectively overcoming the limits of regular statistical analysis methods when dealing with categorical data [65]. It can be applied to small sample size analyses, and the link it constructs between independent and dependent variables is more reliable than classical regression, directly reflecting the explanatory power of the independent variables on the dependent variables. Therefore, Geodetector has the advantage of detecting both numerical and qualitative data and can be used to measure spatial differentiation, detect explanatory factors, and analyze the interaction between variables, which has been widely used in the fields of natural and social sciences [66,67].

Geodetector can be divided into risk area detection, differentiation factor detection, interaction detection, and ecological detection. Among them, differentiation factor detection can effectively identify influencing factors and detect the magnitude of their impact. Interaction detection, on the other hand, can explain the interactive effects of multiple influencing factors on the dependent variable. They are chosen to analyze the driver factors of CCD of the PSR urban flood resilience in this paper.

The differentiation factor detection can effectively detect the impact of specific influencing factors on the CCD of urban flood resilience. The explanatory power of an influencing factor on the CCD of urban flood resilience can be obtained by comparing the total variance of the influencing factor in different cities with the total variance of the factor in the entire region. This is measured using a q-value, and the calculation formula is as follows [63].:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \tag{12}$$

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2 \tag{13}$$

$$SST = N\sigma^2 \tag{14}$$

Where, h = 1, 2, …, represents the city in the study area. L represents the partition of influencing factors or the coupling coordination of urban flood resilience, in this paper specifically referring to the 27 cities in the Yangtze River Delta region. N_h and σ_h represent the number of units and variance within each city h, respectively. N and σ represent the total number of cities and variance in the entire Yangtze River Delta region. SSW and SST represent within sum of squares and the total sum of squares, respectively. The q-value ranges from [0, 1], indicating the explanatory power of the influencing factor on the CCD of urban flood resilience as 100*q%. A higher q-value suggests a greater explanatory power of the influencing factor on the CCD of urban flood resilience.

The interaction detection can explore the interactive effects of different influencing factors on the dependent variable, which is the CCD of urban flood resilience in this case. For example, when evaluating the joint effect of factors X1 and X2 on UFR, it examines whether their combined impact is enhanced or diminished, or whether their effects on the CCD of urban flood resilience are mutually independent.

3.5. Data source

The data for influencing factors of UFR (X1-X3, X5-X10) mainly come from the annual city yearbooks and statistical bulletins of various cities in the YRD region, including "China City Statistical Yearbook," "Jiangsu Province Statistical Yearbook," "Zhejiang Province Statistical Yearbook," "Shanghai Statistical Yearbook," as well as the statistical bulletins of cities from 2015 to 2020. In addition, the data for influencing factor X4 mainly come from the official websites of various city governments, such as the Shanghai Municipal People's Government website (http://www.shanghai.gov.cn/), Nanjing Municipal People's Government website (http://www.nanjing.gov.cn/), Jiangsu Provincial Bureau of Statistics website (http://tj.jiangsu.gov.cn/index.html), etc. The specific descriptive statistics of the influencing factor data are shown in Table 3.

4. Results

4.1. CCD evaluation results

4.1.1. Trend of CCD based on tempo-spatial perspective

(1) Trends of "Pressure-State-Response" three-dimensional CCD

The changing trend of the CCD of flood resilience in the YRD region, based on the Pressure-State-Response framework, is shown in Fig. 5. From a regional perspective, the three-dimensional CCD of flood resilience in the YRD region has experienced minimal fluctuations over the past five years, showing a gradual upward trend. In 2019, it reached 0.3921, indicating a low imbalance but gradually moving towards the stage of primary coordination.

Table 3
Statistical description of influencing indicators.

Influencing Factor	Unit	Max	Min	Average	Standard Deviation
X1	ton	286793	3000	64722.18	54974.91
X2	°C	32.50	26.30	28.97	1.48
X3	item	92460	1040	20250.26	17781.30
X4	%	43.96	8.12	15.72	6.42
X5	10000 yuan	1126162300	6685770	119258146.90	193095735.30
X6	%	13.11	−2.97	3.40	3.15
X7	%	3.73	0.46	1.18	0.61
X8	%	89.60	42.20	65.59	9.58
X9	%	19.53	0.41	3.53	3.53
X10	10000 yuan	126686893	1763730	22496786.49	22613223.58

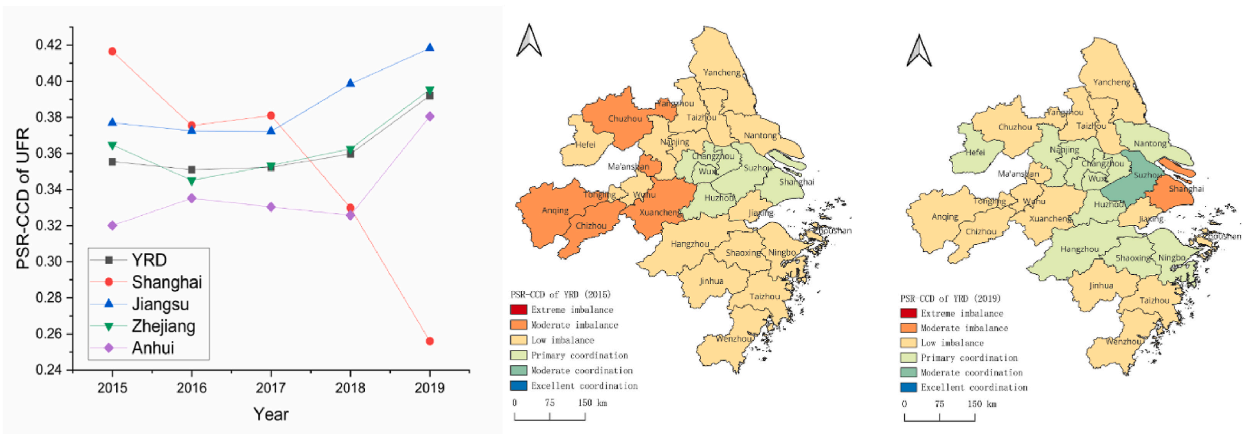

Fig. 5. Trends of "pressure-state-response" three-dimensional CCD of UFR in YRD.

At the provincial level, Jiangsu, Zhejiang, and Anhui provinces have shown an overall increasing trend in the average coupling coordination, while Shanghai has shown a decreasing trend. Over the five-year period, Jiangsu province progressed from a low imbalance to a state of primary coordination. Zhejiang and Anhui provinces still remain in a state of low imbalance, with Anhui province exhibiting larger fluctuations. On the other hand, Shanghai has witnessed a significant decline from a state of primary coordination in 2015 to a moderate imbalance in 2019. This substantial fluctuation indicates an extreme imbalance in the pressure, state, and response dimensions of its urban flood resilience, and this imbalance is widening with each passing year.

At the city level, the CCD of urban flood resilience in various cities of the YRD region fluctuates within the range of 0.2–0.5, indicating a state between moderate imbalance and primary coordination. Most cities have shown an upward trend in their CCD over the past five years, with resilience in pressure, state, and response dimensions developing towards a more coordinated direction. By 2019, the majority of cities had reached a state of low imbalance or primary coordination. However, a few cities, such as Shanghai and Yancheng, have experienced a decreasing trend in their CCD. The decline in Shanghai is more significant than in Yancheng, primarily due to a substantial resilience decrease in the state dimension of these two cities. The development of flood resilience in these cities has been affected by factors such as population growth, economic development, and increased exposure of people and buildings to flood disasters [60]. This has intensified the risk of flood disasters and weakened the capacity to resist such disasters. Additionally, the response capacity has not improved significantly, leading to a decrease in the CCD of these three dimensions.

(2) Trends of “Pressure-State” two-dimensional CCD

At the regional level, the “Pressure-State” coupling coordination exhibits minimal fluctuations and a slight upward trend as shown in Fig. 6. However, it has remained at the stage of primary coordination over the past five years. At the provincial level, Jiangsu, Zhejiang, and Anhui show an increasing trend in the “Pressure-State” CCD, with significant fluctuations. The major change occurred in 2016 when there was a slight decline in the coupling coordination of Jiangsu and Zhejiang due to the severe flood disasters that year [6], which imposed greater pressure on these provinces. On the other hand, Anhui experienced a substantial increase in its coupling coordination, likely due to its relatively better state resilience compared to the other two provinces, resulting in an increased disparity between pressure resilience and state resilience. Shanghai, however, demonstrates a significant decline in the “Pressure-State” CCD, primarily driven by the progressive decline in its state resilience. The weakening of population, economic, and natural state resilience has intensified the flood risk faced by Shanghai [68].

At the city level, most cities show relatively stable changes in the “Pressure-State” CCD, maintaining a primary coordination stage. Some cities, such as Nanjing, Changzhou, Chuzhou, Chizhou, Shanghai, Taizhou, Tongling, and Nantong, exhibit larger fluctuations exceeding 0.1, with some showing an upward trend and others showing a downward trend. The changing trends indicate that resilience in these two dimensions have been in a relatively fluctuating development state, yet they have not progressed in coordination.

(3) Trends of “Pressure-Response” two-dimensional CCD

At the regional level, the CCD of “Pressure-Response” in YRD region exhibits minimal fluctuations and an overall slight upward trend as shown in Fig. 7. Over the five years, it has progressed from a stage of primary coordination to moderate coordination, with a significant increase in 2019. At the provincial level, Shanghai, Jiangsu, Zhejiang, and Anhui provinces all show an increasing trend in the “Pressure-Response” coupling coordination, with Anhui province experiencing relatively larger fluctuations. Jiangsu and Zhejiang have developed from a stage of primary coordination to moderate coordination, while Anhui has progressed from a state of low imbalance to primary coordination. Shanghai maintains an moderate coordination level and is approaching excellent coordination.

At the city level, all cities demonstrate an upward trend in the “Pressure-Response” CCD, with significant growth. The changing trends indicate that the pressure resilience and response resilience of cities in the YRD region are developing in coordination. The gov-

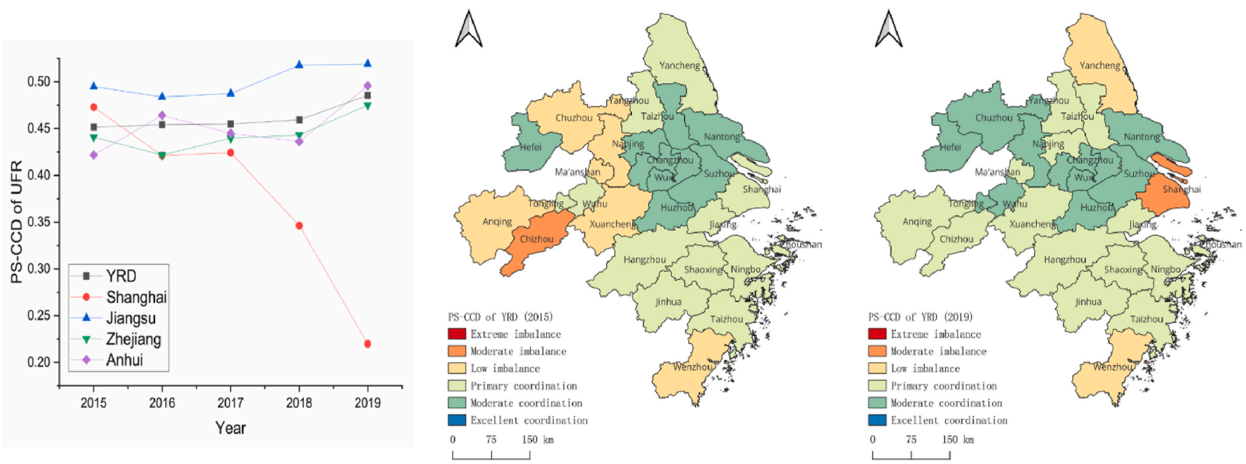

Fig. 6. Trends of“Pressure-State” two-dimensional CCD of UFR in YRD.

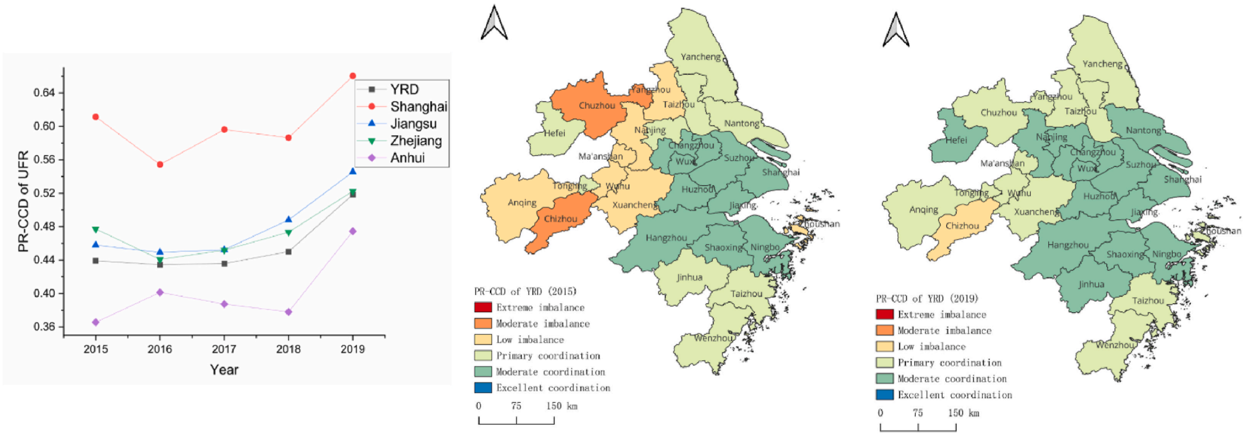

Fig. 7. Trends of"Pressure-Response" two-dimensional CCD of UFR in YRD.

ernment has placed great emphasis on flood disaster management and response, continuously improving the recovery, learning, and adaptive capabilities regarding flood disasters based on the experiences gained from previous years [37].

(3) Trends of "State-Response" two-dimensional CCD

The changing trend of the "State-Response" two dimensional CCD of UFR in the YRD region is shown in Fig. 8. At the regional level, the CCD of "state-response" fluctuates slightly and shows a slight upward trend over the five years, maintaining a primary coordination status, with a significant increase in 2019. At the provincial level, Jiangsu, Zhejiang, and Anhui Province show similar upward changing trends for the period. Jiangsu and Zhejiang maintain a primary coordination status, while Anhui Province transitions from a low imbalance to a primary coordination status. Shanghai, on the other hand, shows a significant decline, dropping from a primary coordination in 2015 to a moderate imbalance in 2019. At the city level, different cities exhibit varying degrees of fluctuation in the "state-response" CCD. Six cities show a downward trend, while the rest show an upward trend. The changing trend indicates that the resilience of the state and response is in a relatively fluctuating development state, and there is still room for improvement in the coordinated development of resistance, recovery, and adaptive capacity and learning ability in dealing with flood disasters.

In general, the coupling and coordination relationships among the "pressure-state-response" dimensions in the YRD region are in a fluctuating state, but they show an overall upward trend, moving towards coordination. Among them, the CCD between "pressure-response" is the highest, and some cities have reached a moderate coordination level, reflecting the attention of governments to flood issues, enabling the coordinated development between resilience in pressure and response dimensions. The CCD between the state and the other two dimensions of resilience, on the other hand, is not high, and some cities even show a downward trend (particularly Shanghai), indicating that as cities' social, economic, and natural subsystems develop, the number of vulnerable elements exposed to flood risk grows. This, to some extent, creates pressure and obstacles for responding to and controlling flood disasters. The resilience of the state dimension becomes a crucial aspect determining the CCD of UFR, which requests that the resilience in this dimension be prioritized.

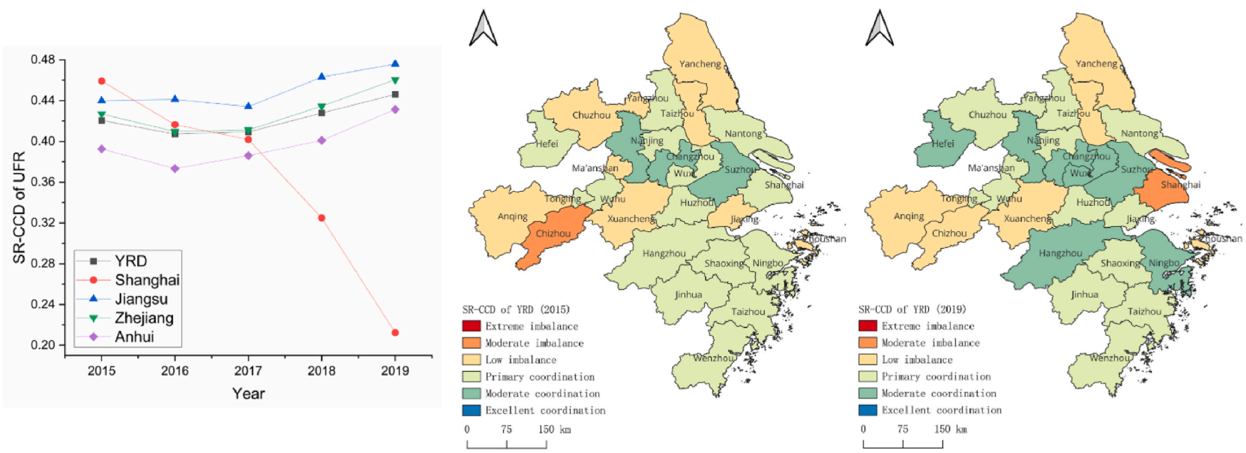

Fig. 8. Trends of "State-Response" two-dimensional CCD of UFR in YRD.

4.1.2. Spatial autocorrelation results

Based on the calculated results of the CCD among different dimensions of UFR in the YRD region from 2015 to 2019, global spatial autocorrelation analysis was conducted using ArcGIS software. The global Moran's I values were obtained for the CCD of “pressure-state-response”, “pressure-state”, “pressure-response”, and “state-response” of UFR in the YRD region for each year. As shown in Table 4, the p-values for the coupling coordination degree of “pressure-state-response” were all less than 0.1, corresponding to Z scores greater than 1.65, indicating significant Moran's I values [61]. Additionally, all the Moran's I values for each year were positive, indicating spatial clustering of the CCD of “pressure-state-response,” where cities with high coupling coordination values tended to cluster with neighboring cities with high values, and cities with low coupling coordination values tended to cluster with neighboring cities with low values, demonstrating a spatial positive correlation pattern. Among them, the Moran's I value for 2017 was the highest, indicating the most pronounced spatial clustering pattern.

Similarly, for the CCD of “pressure-state” and “pressure-response,” the Moran's I values were significant for all the years except 2016. The highest Moran's I value was observed in 2018, indicating the most pronounced spatial clustering pattern. Regarding the CCD of “state-response,” the Moran's I values were not significant in 2015 and 2019. Although significant in other years, the Moran's I values were lower compared to the coupling coordination values of other dimensions, suggesting a relatively less pronounced spatial clustering phenomenon. Overall, the CCD of “pressure-state-response” for UFR in the YRD region exhibited a significant spatial clustering effect with fluctuations observed in different years. The spatial clustering effect of the CCD of “pressure-state” and “pressure-response” was relatively more pronounced compared to the “state-response” dimension.

4.2. Factor analysis results

The spatial differentiation characteristics of CCD among 27 cities in YRD were investigated in geographic detector with results shown in Table 5. From the perspective of the spatial differentiation of the “pressure-state-response” three dimensional CCD (PSR-CCD), except for the citizen growth factor (X6), the detection results of the other influencing factors are all significant. This indicates a significant impact on the coupling coordination relationship of the three dimensions, with the influencing factors ranked as follows: X9 >X10 >X8 > X1 >X3 > X5 >X4 > X2 > X7. Among them, urbanization, air pollution, and technological innovation are the most significant explanatory factors ($q > 0.3$), indicating that the urbanization process, air quality, and technological development in the YRD region are the main factors influencing the PSR-CCD of UFR.

Table 4
Moran's I test of CCD of UFR indexes of the cities in YRD.

Year	2015	2016	2017	2018	2019
CCD of “pressure-state-response”					
Moran's I Index	0.4058	0.2148	0.5570	0.5020	0.2337
Z Score	3.5085	1.9646	4.6558	4.1841	2.1330
P Value	0.000	0.049	0.000	0.000	0.032
CCD of “pressure-state”					
Moran's I Index	0.4057	0.1635	0.4051	0.4458	0.1991
Z Score	3.5085	1.5585	3.5695	3.8117	1.9605
P Value	0.000	0.119	0.000	0.000	0.049
CCD of “pressure -response”					
Moran's I Index	0.4986	0.1485	0.5435	0.5728	0.3475
Z Score	4.2029	1.4455	4.5283	4.6784	2.9781
P Value	0.000	0.148	0.000	0.000	0.002
CCD of “state-response”					
Moran's I Index	0.0717	0.2657	0.2175	0.2737	0.1261
Z Score	0.8561	2.3503	1.9866	0.2406	1.3221
P Value	0.392	0.018	0.046	0.016	0.186

Table 5
Factor detection results of CCD of UFR in YRD.

No.	q statistic for PSR-CCD	q statistic for PS-CCD	q statistic for PR-CCD	q statistic for SR-CCD
X1	0.3609***	0.2137*	0.3230***	0.3357***
X2	0.1689**	0.0484	0.2151***	0.1859***
X3	0.3417***	0.0671	0.4968***	0.3804***
X4	0.2943***	0.2164***	0.0946*	0.3956***
X5	0.2974*	0.1098	0.4159***	0.4097***
X6	0.0358	0.0416	0.0248	0.0816*
X7	0.1595*	0.0779	0.1360*	0.1648**
X8	0.3682***	0.1644***	0.3993***	0.3491***
X9	0.3927***	0.3667***	0.3402***	0.3387***
X10	0.3790***	0.0763	0.5599***	0.3955***

Note: *** indicates a significant correlation at the 0.001 level (two-tailed); ** indicates a significant correlation at the 0.01 level (two-tailed); * indicates a significant correlation at the 0.05 level (two-tailed). PSR-CCD refers to the “pressure-state-response” three-dimensional CCD. PS-CCD refers to the “pressure-state” two-dimensional CCD. PR-CCD refers to the “pressure-response” two-dimensional CCD. SR-CCD refers to the “state-response” two-dimensional CCD.

In terms of the “pressure-state” two-dimensional CCD, urbanization level, government administrative capacity, and air quality are the main factors influencing the coupling coordination of resilience in pressure and state. The order of influence is X9 > X4 > X1 > X8, while the effects of other influencing factors are not significant. It can be observed that the PS-CCD is mainly influenced by natural and social factors, including urban planning and layout, government governance efforts, and pollution control.

Apart from population growth, all other influencing factors have varying degrees of impact on the “pressure-response” two-dimensional CCD. The order of influence is X10 > X3 >X5 > X8 >X9 > X1 > X2 > X7 > X4. Among them, total retail sales of social consumer goods per capita which represents the economic urbanization has the greatest impact ($q > 0.5$), followed by technological innovation and financial strength ($q > 0.4$). It can be observed that the level of urban economic development is the most crucial factor influencing the PR-CCD. The stronger the economic power, the more resources can be allocated for manpower and materials in response to and recovery from flood disasters [68]. Utilizing various technological means to mitigate the impact of flood disasters, cities can better cope with disaster pressure, respond effectively, and learn from flood disasters [60].

From the perspective of the “state-response” two-dimensional CCD, various factors exert different degrees of influence. The order of influence is as follows: X5 > X4 > X10 > X3 > X8 > X9 > X1 > X2 > X7 > X6. Among them, financial strength (X5) has the greatest impact ($q > 0.4$), and other socio-economic factors such as governance power and technological innovation also have significant effects. It can be seen that the interaction between urban economic development, natural ecology, and socio-economic factors is the most important factor influencing the CCD of the state and response in UFR.

In summary, the urbanization in population, land, and economy (as interactions between the natural ecological system and the socio-economic system) are the most significant factors influencing the PSR-CCD of UFR. Except for economic urbanization (X10), which has an insignificant impact on pressure-state CCD, the remaining influences exceed 0.3, indicating a substantial explanatory power and important impact on the development of the three dimensions of the CCD for UFR. Furthermore, socio-economic factors have a significant influence on explaining the coupling coordination between state and response resilience. This highlights that the response and governance of urban flood disasters still largely depend on social development and economic strength. The development of urban flood resilience relies on the coordinated progress of socio-economics [69]. Additionally, the influences of air pollution and global warming should not be overlooked. They have a significant impact on the PR- CCD, reflecting the outcomes of human-nature interactions and serving as important factors leading to frequent flood disasters [70]. Therefore, they require focused attention when enhancing urban flood resilience.

4.3. Interaction detection results

The multi-factor interaction of PSR-CCD, as shown in Fig. 9(a), exhibits a strengthening relationship between each factor. The interaction effect is significantly greater than the individual effect of each factor (with most q values exceeding 0.5). The result indicates that the interaction between each pair of factors enhances the explanatory power of the spatial differentiation of “pressure-state-response” coupling coordination. The analysis of the CCD between the pressure, state, and response dimensions of UFR is the result of the combined effect of multiple factors. Among them, the synergistic effect between air pollution (X1) and urbanization in population (X8) is the most pronounced ($q = 0.6226$), far exceeding the explanatory power of individual factors ($q\ (X1) = 0.3609$, $q\ (X8) = 0.3682$). The synergistic effect of land urbanization (X9) and economic urbanization (X10) is also significant ($q > 0.6$), and their interaction mutually reinforces the promotion of PSR-CCD.

The multi-factor interaction of the PS-CCD, as shown in Fig. 9(b), exhibits a strengthening relationship between each factor. This indicates that the interaction between each pair of factors enhances the explanatory power of the spatial differentiation of PS-CCD. The synergistic effect between air pollution (X1) and financial strength (X5) is the most pronounced ($q = 0.5225$). This suggests that the synergistic interaction between the natural ecological system and the socio-economic system significantly influences the spatial differentiation of PS-CCD.

The multi-factor interaction of the PR-CCD, as shown in Fig. 9(c), exhibits a strengthening relationship between each factor. The interaction effect is significantly greater than the individual effect of each factor (with most q values exceeding 0.5). This indicates that the interaction between each pair of factors enhances the explanatory power of the spatial differentiation of PR-CCD. Among them, the synergistic effect between global warming (X2) and economic urbanization (X10) is the most pronounced ($q = 0.6526$). The synergistic interactions between other factors and economic urbanization are also relatively high. The synergistic interactions between technological innovation (X3) and citizen growth rate (X6), as well as technological innovation (X3) and stakeholders (X7), are also relatively high. This indicates that climate change, urban economic development, technological innovation, and population development significantly influence the spatial differentiation of PR-CCD.

The multi-factor interaction of the SR-CCD, as shown in Fig. 9(d), also exhibits a strengthening relationship between each factor. The interaction effect is significantly greater than the individual effect of each factor (with most q values exceeding 0.5). This indicates that the interaction between each pair of factors enhances the explanatory power of the spatial differentiation of SR-CCD. Among them, the synergistic effect between air pollution (X1) and financial strength (X5) is the most pronounced ($q = 0.6792$), demonstrating a dual-factor enhancing effect. Furthermore, there are relatively high synergistic interactions between air pollution (X1) and governance power (X4), technological innovation (X3) and X4, X5 and X4, X4 and population urbanization (X8), X4 and land urbanization (X9), X5 and X8, X5 and X9, number of relevant actors (X6) and X8, and X9 and economic urbanization (X10). Together, they influence the spatial differentiation of SR-CCD.

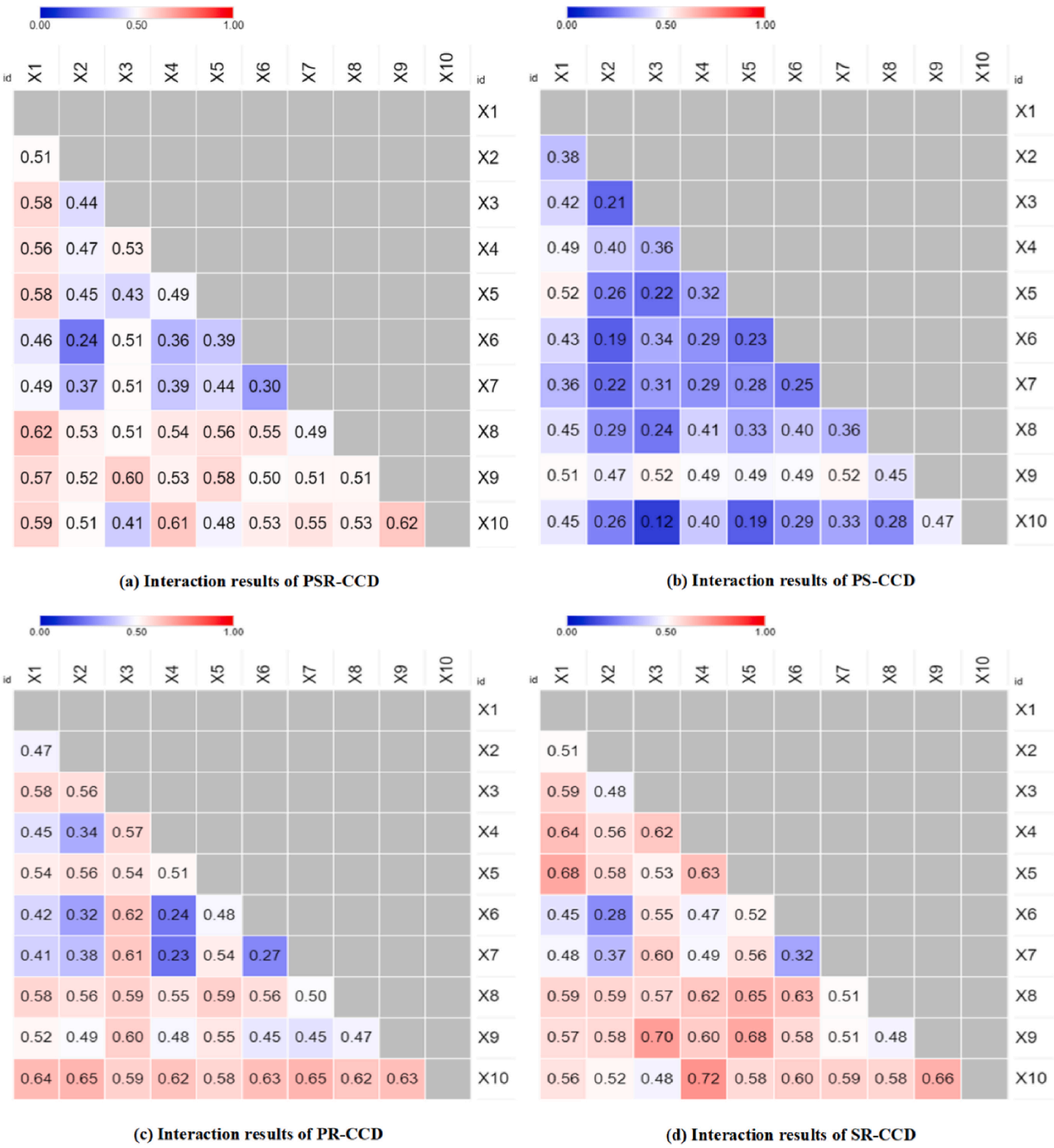

Fig. 9. Multi-influencing factor interaction results of CCD for UFR in YRD.

5. Discussion and implications

5.1. Key driving factors

Based on the analysis of the intensity of factors and their interactive effects, the spatial differentiation of CCD for UFR is influenced by several dominant factors. By considering the magnitude of influence, significance, and interaction analysis, the main influencing factors for the spatial differentiation of each type of CCD can be inferred, leading to corresponding improvement strategies, as shown in Table 6. The dominant influencing factor for the PSR-CCD is the interaction among urban subsystems. The coordinated development of the three dimensions requires consideration of the impact of current urbanization construction, the influence of human activities on the natural ecology, reduction of greenhouse gas emissions, and the promotion of new kinds of urbanization construction.

Table 6
The key driver factors.

CCD type	key driving factors	Main interactions	Factor type
PSR-CCD	X8, X9, X10	X1 and X8	Interaction between two systems
PS-CCD	X1, X3, X9	X1 and X5	Natural-ecological system
PR-CCD	X3, X5, X10	X2 and X10	Social-economic system
SR-CCD	X4, X5, X10	X1 and X5	Social-economic system

The key driving factors contributing to the spatial differentiation of PS-CCD often originate from the natural ecological system. Since UFR in pressure dimension primarily relies on natural perspective, the significant inducers of flood disaster risks are air pollution and global warming. Therefore, PS-CCD for UFR needs to focus on the natural system, including pollution control, reduction of flood disaster risks, and protection of the ecological environment.

On the other hand, the dominant factors influencing the spatial differentiation of PR-CCD primarily stem from the social and economic system. Technological innovation and economic development are the main means to enhance UFR in response dimension. The PR-CCD requires leveraging intelligent capabilities, developing new technologies for flood disaster management, and implementing scientific flood control measures. Regarding the spatial differentiation of SR-CCD, the key driving factors also mainly originate from the social and economic system. Emphasis is placed on a city's economic strength and governance power. It is necessary to build a foundation of economic development, strengthen the government's capacity and level of flood disaster management, maintain a good state for coping with flood disasters, and continuously improve disaster response, recovery, and learning capabilities.

5.2. *Possible implications*

The analysis of CCD for UFR in section 4.1 reveals severe challenges. At the regional, provincial, and municipal levels, the PSR-CCD is mostly in a state of imbalance, representing the current shortcomings. The PS-CCD, as well as the SR-CCD, is relatively low, highlighting the critical deficiencies that affect overall coupling coordination. This also represents the current YRD regional development process's existing imbalances in population, resources, and environmental development, needing priority attention and solutions. The spatial distribution of CCD for UFR in the YRD region also exhibits certain variations. The central region has stronger urban coupling coordination, but the region's outer periphery has comparatively low coordination, generating an engulfing tendency towards the central region.

Therefore, in terms of both the level and spatial distribution of UFR coupling coordination, cities in the YRD region are in a state of imbalance, deviating significantly from the requirements of regional integration. This represents a significant gap that needs targeted solutions. However, it is important to acknowledge the objective existence of uneven economic and natural conditions among different cities (S. Zhu, Li et al., 2023). Resolving the coupling coordination issues should adhere to economic and natural laws, be tailored to local conditions, provide categorized guidance, recognize objective differences, and combine static and dynamic measurements of urban flood resilience to apply appropriate measures [60,68,69].

Based on the above analysis and results, with the help of the proposed conceptual framework, it is necessary to comprehensively consider the interactions between natural-ecological system and social-economic system. Possible implications are demonstrated as follows.

5.2.1. *Implications for natural-ecological system*

The findings from factor analysis indicate that air pollution (X1) and global warming (X2) in natural-ecological system are important drivers of CCD for UFR in the YRD region and should be prioritized. They also have interactions with other driving factors for CCD in PSR, PS, PR and SR as shown in Table 6. Currently, global climate change is still primarily associated with greenhouse gas emissions [71,72]. The deposit of the ratification documents of the Paris Agreement in 2016 took place in Hangzhou, a city in Zhejiang Province in the YRD region [73]. Participating countries collectively committed to relevant greenhouse gas emission reduction targets. Reducing greenhouse gas emissions caused by human activities can not only mitigate climate change and reduce the risk of flood disasters [74], but also bring about broad health benefits, including saving lives, preventing diseases, and increasing life expectancy [75]. In this regard, it is necessary to continue implementing relevant policies and indicators for carbon emission reduction and pollution control. It is important to establish carbon pricing mechanisms and implement carbon taxation systems to drive employment opportunities in cleaner, more environmentally friendly, and greener economic sectors [76]. The carbon emissions trading system's primary role should be exploited to ensure its successful promotion of greenhouse gas emission reduction and full play of its role in total greenhouse gas emission control and meeting the peak target [77]. Active exploration of new areas for energy conservation and emission reduction should be pursued, including research into personal carbon trading, digital carbon trading and contract energy management mechanisms.

5.2.2. *Implications for social-economic system*

Technology and innovation related factor (X3) in social-economic system is also an important driving factor directly influence the PR-CCD and PS-CCD of UFR in YRD regions. This suggests that modern technologies and techniques can assist in making strategic, comprehensive, and intelligent flood mitigation decisions by summarizing previous experience, diagnosing the current condition, and anticipating future trends. For example, with the development of information technology and the networked society, smart city construction provides innovative technologies, ideas, and channels to enhance urban flood resilience [78]. Cities should strengthen the construction of foundational information infrastructure such as 5G, cloud computing, Artificial Intelligence (AI), the Internet of Things (IoT), and smart terminals [79,80]. By utilizing big data technology, they can facilitate cross-departmental, cross-level, and cross-regional sharing of flood-related information, knowledge, and data. This includes building digital disaster simulation and experimental platforms and applying innovative technological approaches to achieve effective pre-control, swift response, and efficient post-disaster rescue measures for flood events [81].

Governance power (X4) has been shown to be a driving element for SR-CCD, and financial strength (X5) has an effect on both PS-CCD and SR-CCD, as well as an interaction effect with air pollution (X1) in these two areas. The findings imply that economic development remains the most important factor in increasing UFR which is consistent with other studies [9,51], [60], and the trade-off between economic expansion and air pollution should be highlighted. In the *Report to the 20*th *National Congress of Communist Party of*

China, it is mentioned that a green and low-carbon economy and society are crucial to high-quality development. In order to carry out coordinated industrial restructuring, pollution control, ecological conservation, and climate response, China will promote concerted efforts to cut carbon emissions, reduce pollution, expand green development, and pursue economic growth [82]. That's the guide for the green economy development of YRD regions. Besides, to promote the CCD of UFR, government also needs to improve the institutional resilience, including making scientific decisions, adopting unified deployment and smart approaches, and allocating responsibilities according to the duties outlined in emergency response plans [83]. Active participation in emergency response and rescue operations is crucial, along with the effective implementation of decisions and deployments made by higher authorities [84,85]. It is important to ensure a smooth and flawless process in every aspect. Therefore, strengthening organizational resilience can help to enhance communication and coordination, as well as the government's execution and governance capabilities.

5.2.3. Implications for the interactions

Urbanization in population, land, and economic (X8, X9 and X10) are important factors that affect the three-dimensional CCD of urban flood resilience and their interactions. The improvement strategy needs to focus on the direction of urbanization construction and development. Practically, the *Key Tasks for New-Type Urbanization Construction and Urban-Rural Integration Development* in 2020, issued by the National Development and Reform Commission (NDRC) (Development and Reform Planning [2020] No. 532), requires accelerating the development of key urban agglomerations, optimizing the spatial pattern of urbanization, leveraging the comparative advantages of different regions, enhancing the ecological carrying capacity of economically developed regions, and constructing a coordinated development spatial pattern of large, medium, and small cities [86]. Currently, the YRD region is centered around the mega-city of Shanghai, with prominent positions of major or large cities such as Nanjing, Suzhou, Wuxi, Hangzhou, Ningbo, and Hefei, forming a distinct hierarchical urban system. With the increasing dependence of future urban population and employment on central cities and urban agglomerations [87], it is necessary to coordinate population demand and resource pressure, tackle the structural contradiction between insufficient resources and increasing demand, and establish effective ecological supplementation systems. It is important to explore pathways and employ strategies for high-quality sustainable development in various aspects, including society, economy, and nature [88,89].

5.3. Limitation and future directions

This paper builds a new framework for analyzing the interactions between three dimensions of urban flood resilience. Most of the indicators in this model are derived from yearbooks, reports, and government websites. The measurement of urban flood resilience is carried out using secondary data and annual geospatial data, which, to some extent, facilitates data collection and processing, thus improving timeliness and practicality. However, relevant indicators, such as the specific scope, depth, and duration of rainfall impact, organizational coordination in flood disaster management, as well as characteristics, emotions, and participation of residents, can only be obtained through primary research. Besides, the strategies formulated in section 5.2 are more oriented from the government perspective. In practice, enhancing urban flood resilience requires a multifaceted cooperative strategy involving “government leadership, corporate support, and citizen participation” [90][91]. Therefore, future research can focus on analyzing the communication, connections, cooperation, and conflicts among various social actors throughout the disaster process. Following this analysis, a social network model or a multi-agent simulation model can be built to simulate the interactive evolution of these social actors. Then, enhancement strategies from the perspectives of key stakeholders in urban flood resilience can be proposed, with a focus on entities like the government, residents, businesses, volunteers and more.

6. Conclusion

To depict the interconnectedness between different urban systems and enhance flood resilience, this paper adopts a combined approach of the PSR and SES framework. The conceptual framework is constructed to analyze urban flood resilience, utilizing cities in the YRD area as an illustrative example. Building upon previous research, twenty-four indicators derived from the PSR framework are employed for tempo-spatial coupling coordination analysis. Ten indexes representing the natural-ecological system, social-economic system, and their interactions are identified as influential factors. To identify key driving factors, the Geodetector model is employed for factor analysis and interaction detection. The findings reveal that the coupling and coordination relationships among the dimensions of “pressure-state-response” in the YRD area exhibit variability but demonstrate an overall upward trend towards coordination. Notably, the resilience of the state dimension emerges as a crucial aspect that determines the CCD of UFR, emphasizing the importance of prioritizing resilience in this dimension. Furthermore, the interactions between the natural-ecological system and the social-economic system are identified as dominant factors influencing the CCD of PSR for UFR in the YRD area. This highlights the significance of considering and fostering interactions between these systems for effective urban flood resilience. Last, possible implications and suggestions for each interaction detection are discussed and illustrated.

The paper provides insights contributing to a deeper understanding of the interconnectedness and dynamics between urban natural-ecological and social-economic systems and the promotion of urban flood resilience through a pressure-state-response cycle. The findings derived from this research offer valuable guidance for decision-makers and practitioners involved in urban planning, disaster management, and resilience-building endeavors. It is important to note, however, that precise proposals may require further investigation into the specific local urban conditions, as they may vary from city to city. The coordination relationship and influencing factors identified in this study can serve as a foundation for examining and validating their applicability in diverse geographical areas with varying urban contexts. By conducting similar analyses in various locations, we can gain a comprehensive understanding of the dynamics and relationships between urban systems and their impact on flood resilience. This will facilitate the proposal of context-specific implications for local situations, tailoring strategies to meet the unique needs and challenges of each area. Furthermore, in future research, the interaction paths presented in this study can be evaluated using simulation approaches, allowing for a more comprehensive assessment of its effectiveness and applicability.

CRediT authorship contribution statement

Shiyao Zhu: Conceptualization, Data curation, Investigation, Methodology, Software, Visualization. **Haibo Feng:** Resources, Supervision. **Mehrdad Arashpour:** Writing – review & editing. **Fan Zhang:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Table A1
Details for PSR variables.

Dimensions	Indicators	Explanations
Pressure		
Natural pressure	I1 Annual Precipitation	Annual precipitation for the city.
	I2 Max precipitation in 24 h	Max precipitation in 24 h of the year.
	I3 Flood risk	Percentage of precipitation in 24 h over 50 mm over all raining days of the year.
	I4 Elevation, slope and aspect	Superposition results of elevation, slope and aspect of the city by GIS.
State		
Social state	I5 Aging degree	Percentage of people over the age of 60.
	I6 Children percentage	Percentage of people under the age of 15.
	I7% of population exposure to floods	Population per unit area of urban land that may be affected by flooding.
Economic state	I8 Per capita GDP	Per capita GDP of the city.
	I9 Residents' economic status	The difference between total household income and expenditure as a percentage of total household income.
	I10 Employment status	Employment rate in the city.
Natural state	I11 Drainage network	Density of drainage pipes in built-up areas.
	I12 Green coverage	Percentage of green space area in the urban land.
	I13 Urban road condition	Exposure of urban road during the flood.
Response		
Social response	I14 Early warning ability	Flood prediction accuracy.
	I15 Emergency management ability	Emergency management ability of city.
	I16 Knowledge learning ability	Flood disaster knowledge learning ability of the city.
	I17 Public reaction ability	The public's ability to independently judge, rescue and recover from flood disasters.
Economic response	I18 Urban maintenance and construction budget	Urban maintenance and construction budget of the city.
	I19 Flood insurance	Flood insurance coverage of the city.
	I20 Economic diversity	Proportion of tertiary industry.
Natural response	I21 Water and power supply	Water and power supply of the city.
	I22 Public transportation service capacity	Public transportation service capacity of the city.
	I23 Communication capacity	Percentage of mobile telephones and Internet subscribers at the end of year.
	I24 Medical aid capacity	Hospital beds coverage of the city.

Note: Adopted from previous studies [58]; [54]; [10].

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