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Geographical Impact and Ecological Restoration Modes of the Spatial Differentiation of Rural Social-Ecosystem Vulnerability: Evidence from Qingpu District in Shanghai

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Abstract: Vulnerability research is the core issue and one of the research hotspots of sustainable development science. Vulnerability and its evaluation framework provide a new perspective for rural social-ecosystem studies. This paper introduced the 'input-output' efficiency theory and constructed the 'SEE-PSR' framework for the analysis of social-ecosystem vulnerability in the rural area in Qingpu District of Shanghai City. The DEA models, spatial autocorrelation model, multivariate logistic regression model, geographical detector and hierarchical cluster model were used to analyze the spatial differences of social-ecosystem vulnerability, and its geographical impact mechanisms and ecological restorations, in 184 administrative villages in this area. The results can be divided into three main points. (1) The results of the 'input-output' efficiency model of the EW-DEA based on entropy weight aggregation crossover was more reliable and accurate for the evaluation of rural social-ecosystem vulnerability. The vulnerability of the social-ecosystems in the administrative villages showed a trend of gradual decline from east to west, with an average value of vulnerability of 0.583, and the vulnerability of social systems had become an important factor in constraining the decrease of the vulnerability of the social-ecosystems in the region. (2) The distances from the center of Shanghai City, from Dianshan Lake, from the center of Qingpu District and from the water area were the four dominant geographical factors affecting the vulnerability of the social-ecosystem in this region. The geographical impacts exhibited the spatial differentiations of systemic structure, the substitution of typological attributes and the transformation level. (3) The geographical factors coupling the impact types of the social-ecosystem vulnerability were divided spatially into 10 types. The geographic multi-factor coupling impact types were dominant, which presented multi-cyclic spatial patterns and were dominated by the central multi-factor which was surrounded by the single factor types on both sides. According to the different types, some feasible ways of ecological restoration were proposed, which drew on the experiences of integrated territory consolidation to remediate the vulnerability of rural social-ecological systems. The results of this study can provide scientific reference for rural spatial reconstruction, regional ecological restoration and sustainable development for the regions characterized by conflict in the 'strict protection of the ecological environment and vigorous development of the economy'.

Key words: social-ecological system; vulnerability evaluation; efficiency; geographical factors; geographical impact modes; ecological restoration; Qingpu District

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1 Introduction

Vulnerability is a systemic attribute which can easily damage the structures and functions, and manifest the interactions between tolerance and resilience, of a system or systemic components in ways which limit that system's ability to cope with risks (Timmerman, 1981). Vulnerability is a hotspot and frontier in the study of regional sustainable development (Cumming et al., 2017; Grimm et al., 2017). Changes in the social-economic environment have brought unprecedented challenges to regional social-ecosystems, and they have driven the relatively stable closed systems, which had been in a low equilibrium for a long time, to become open systems that deviate from equilibrium, which has a profound impact on the development of agriculture, rural areas and farmers in the region (Chaffin et al., 2016; Melnykovych et al., 2018). As affected by the great pressures of rapid urbanization, industrialization and modernization, the rural social-ecological systems have gradually exposed their vulnerability to the changes of environmental pressures. That is, the vulnerable state of the rural social-ecosystem, which was not conducive to the stability of its systemic structure and function, and the responses of the subject, object and environment to the pressure after facing the disturbance and the disturbance of the environmental change, were presented (Apotsos, 2019). As a representation of regional natural and economic location attributes, the geographical factors are closely related to the social-ecosystem, which can either increase or reduce the vulnerability of the rural social-ecosystem (Rajesh et al., 2018). The water conservation area in the urban suburbs has an extremely superior geographical and economic location, and its social-ecological system is the most directly impacted and sensitive to the social and economic pressures. On the one hand, as the frontier position of urbanization, industrialization and modernization, urban suburbs had promoted the rapid deconstruction of relatively closed rural systems into open systems that deviate from or are far from equilibrium through energy flow, logistics and information flow in the process of social and economic transformation. On the other hand, water conservation areas with strong rural regional attributes, inherent rural structural endowment and water area labels, under pressure, have vigorously maintained the closed state of the social-ecosystem, which has hindered the degree and rate of opening of those systems. Therefore, assessing the vulnerability of social-ecosystems in the village area of an urban water source area, and analyzing the regional differentiation mechanism under the influence of its spatial characteristics and geographical factors, is of great scientific research value and social significance for reducing the vulnerability of social-ecosystems in conflicted regions.

As the core problem of sustainable development science, vulnerability is mainly focused on the following aspects under the promotion of international research programs such as IHDP, IPCC, and IGBP. 1) The contents of vulnerability research have been extended from the vulnerability concept and theoretical construction (Huynh et al., 2018) to the single system vulnerability and coupling system vulnerability (Rajesh et al., 2018), such as disaster systems (Adger et al., 1999), ecosystem vulnerability (Berrouet, 2019), water environment system vulnerability (He et al., 2016), social system vulnerability (Abid et al., 2016), economic system vulnerability (Peng et al., 2015) and so on. 2) The dimensions of vulnerability quantification have been extended from qualitative analysis of the impact factors and impact mechanisms of systemic vulnerability (Angeon et al., 2015) to the integrated evaluation by means of an index system systemic vulnerability (Liu et al., 2013). 3) Multiple methods coupled to evaluation and comparison with systemic vulnerabilities have become a trend, such as SEE-BP Neural Networks (Wang et al., 2018), DPSIR-SPA (Li et al., 2013) and so on. 4) Case areas for vulnerability are concentrated in poor mountain areas with fragile natural geography (Maikhuri et al., 2017), coastal areas (Peng et al., 2015), ecological lake areas (Wang et al., 2018), tourist destinations (Chen et al., 2015), rural regions (Chen et al., 2016) and so on. However, the above studies still have several shortcomings. 1) Regarding the social-ecosystem vulnerability as the risk and loss of system exposure to the adverse environment, it is often evaluated by using the "exposure-sensitivity-adaptation" index. While the above indexes emphasize the explicit appearance characteristics of the social-ecosystem when it is impacted by the external environment, this is not the intrinsic essence of the system vulnerability, and neglects the influence of the subsystem structure on the overall vulnerability of the system. 2) There is a tendency to use the index system synthesis approaches to assess social-ecosystem vulnerability based on specific models. However, these methods rely excessively on weights to integrate various indicators, ignoring the logical relationships among indicators, resulting in the weakening of vulnerability formation mechanisms and the credibility of the evaluation results caused by the methods of weight selection. 3) It tends to associate social-ecosystem vulnerability with poverty factors, forming a more mature logical orientation of 'geographical environment restriction–slow social development–economic backwardness–pressure disturbance–systemic vulnerability'. This research paradigm regards poor geographical environment as the default premise of regional poverty and system vulnerability, which becomes an important basis for selecting the typical case areas. As the inherent endowment characteristics of the region, geographical factors play an important role in the systemic vulnerability caused by the disturbance of the region and causing the regional system to deviate from the equilibrium state. However, poverty and development are two important issues for the region (Chaffin et al., 2016). Under the pressure of great economic interference and rapid social change, the social-ecological system in the economically developed region is far from the equilibrium state, which may also cause the structural damage of the system and form the vulnerability. Therefore, there are some questions which need to be further studied. 1) Is there still an impact of geographical environmental factors on the vulnerability of social-ecosystems in economically developed regions? 2) If so, how do they affect social-ecosystem vulnerability? What is the impact mechanism of its vulnerability? If the impact is not significant, do these geographical factors change?

2 Rural social-ecosystem vulnerability analysis

Rural social-ecosystem vulnerability covers multiple dimensions and is the result of a combination of social vulnerability, economic vulnerability and ecological vulnerability (Chen et al., 2015). As influenced by the openness, comprehensiveness and dependability of the systematic characters, the structure, state and function of the regional social-ecosystem are vulnerable to the disturbances of the internal and external environment. It is implied in the subject and object of the system, and its external manifestation is system risk, exposure, coping forces and recovery forces, which are the quantitative changes of side effects in the development of the system (Cannon et al., 2010). According to the above system evolution mechanism, the social-ecological system process conforms to the 'Pressure-State-Response' analysis framework (Barry et al., 2006; Jerry et al., 2015). Therefore, drawing on the theoretical basis (IPCC, 2007) and vulnerability PSR analysis of Risk-Hazards (Maikhuri et al., 2017), the definition of regional social-ecosystem vulnerability is as follows. In order to reduce the loss of social-ecosystems caused by disturbance, and in the circumstances of objective pressures produced by the external disturbances on the specific social-ecosystems and the conduction of different carriers, the related carriers show the comprehensive state and forces according to their own resources, structures, management methods and so on.

Urban suburbs, which are in the frontier position of urbanization, industrialization and modernization, promote the rapid deconstruction of relatively closed rural systems through energy flow, logistics and information flow in the process of social and economic transformation into open systems that either deviate from or stay away from equilibrium, and the process of system vulnerability is more representative (Fig. 1). 1) Multi-pressure coupling leads to the superposition of vulnerability risk factors in rural social-ecosystems. In the process of rapid urbanization, industrialization and modernization, the states of society, economy and resources have changed sharply, which has caused great disturbance to the suburbs of the city. These disturbances include the rapid expansion of total economic volume and construction land scale, the sharp decline of ecological resources, the surge of the total population, the acceleration of agricultural population transfer and industrial transformation, the regional differences in the allocation of funds, and so on. At the same time, the openness of the urban suburban system, industrial relevance and regional functional symbiosis lead to multi-factor coupling to produce the resource-population-economy-society vulnerability coupling pressures. 2) Multi-path conduction leads to the environmental sensitivity of the rural social-ecosystems. The multidimensional pressures were transmitted between differentiated systems through the property right path, manpower path, financial path and industrial path, which formed the risks of the land and public property right system, the risks of human resources and innovation drive, the risks of the financial system and industrial capital, and the risk of food security and human/land separation. The above risks exacerbated environmental sensitivity to some extent. 3) The association of geographic multi-factors resulted in rural social-ecosystem exposure. Many kinds of system risks were transmitted among regional carriers through differentiated geographical resource endowments, resulting in the loss of the rural population and the disappearance of culture, the pollution of agricultural production capacity and the agricultural environment, the insufficient coverage of public services, the poor accessibility and connectivity of public space, the idle and waste of resources, the similarity of industrial structures, and the imbalance of urban and rural synergy. 4) Finally, the differences of multiple decompression modes resulted in rural social-ecosystem adaptability. According to their own resources and structures, the relevant regional carriers actively regulate economic, social and ecosystem vulnerabilities by means of passive application and management methods, such as sorting, development, restoration, governance and protection, to produce comprehensive resistance, adaptability and resilience in order to reduce the vulnerability of the regional social-ecosystems.

3 Materials and methods

3.1 Study area

The case study area is situated in Qingpu District, a typical suburban district located on the west of Shanghai, bordering Zhejiang Province and Jiangsu Province. Qingpu extends over approximately 668 km^2 and is divided into three sub-districts and eight towns, consisting of 184 villages in total. According to the Qingpu Planning and Land Resources Bureau (http://prog.shqp.gov.cn/), Xiayang, Yingpu, and Xianghuaqiao are three sub-districts in the urban center of Qingpu, with Zhujiajiao, Liantang, and Jinze on the west wing, and Baihe, Chonggu, Zhaoxiang, Huaxin, and Xujing on the east wing (Fig. 2).

Shanghai City is the largest city and the most economically prosperous region of China, being the major economic, financial, trade and shipping center on the Chinese east coast. In 2018, the land area of Shanghai comprised 0.09%

of China and the population was less than 2.1%, but its gross domestic product (GDP) accounted for 4.2% of China's overall GDP (NBSC, 2019). Shanghai has experienced rapid economic development since the beginning of the 1990s. From 1990 to 2018, its resident population grew from 13.34 million to 37.90 million, while the GDP increased from 781.66 billion yuan to 20181.72 billion yuan (NBSC, 2009; NBSC, 2019). Rapid urbanization and industrialization have had profound influences on the development of the suburban rural areas.

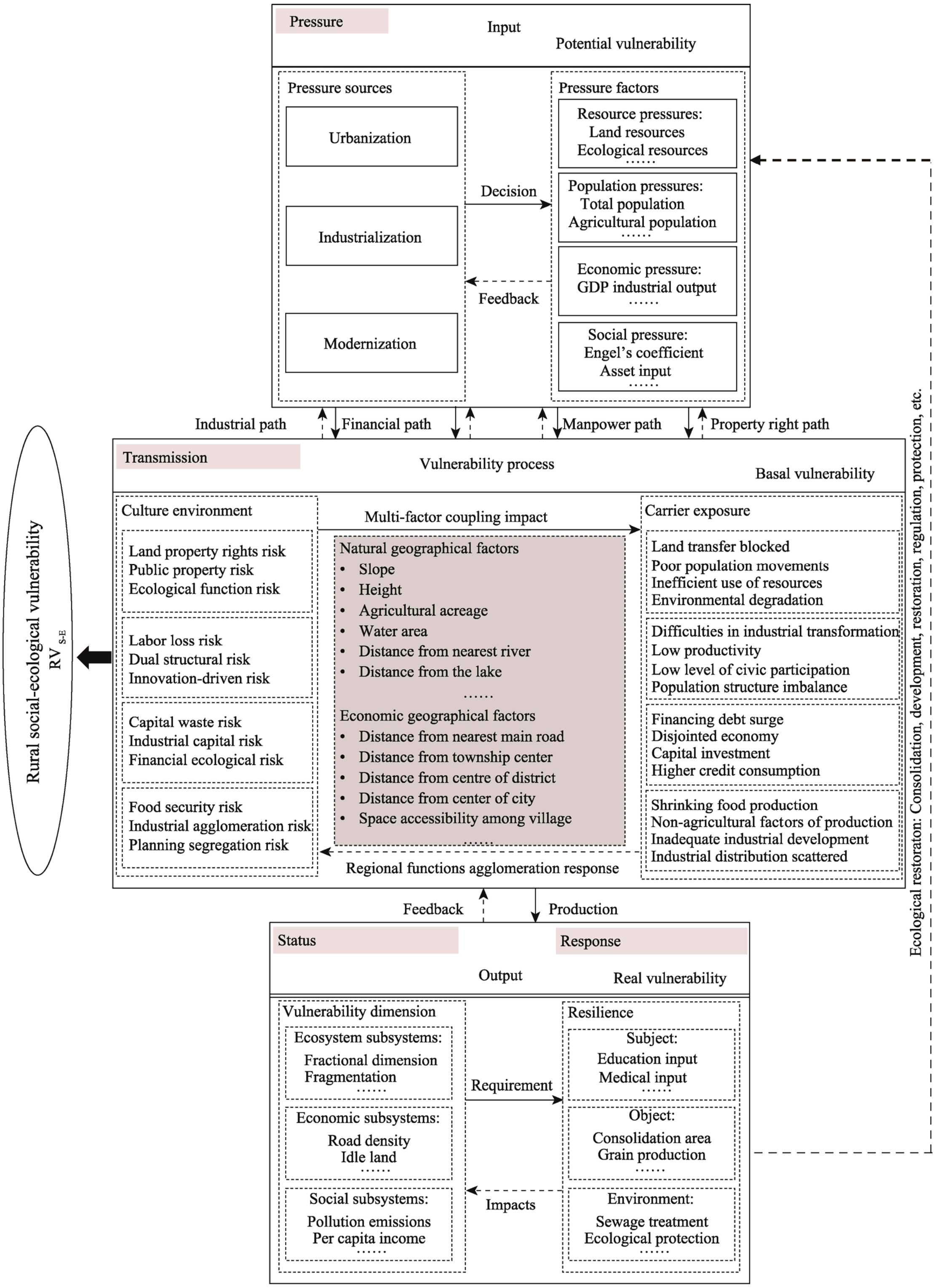

Fig. 1 The framework of rural social-ecosystem vulnerability

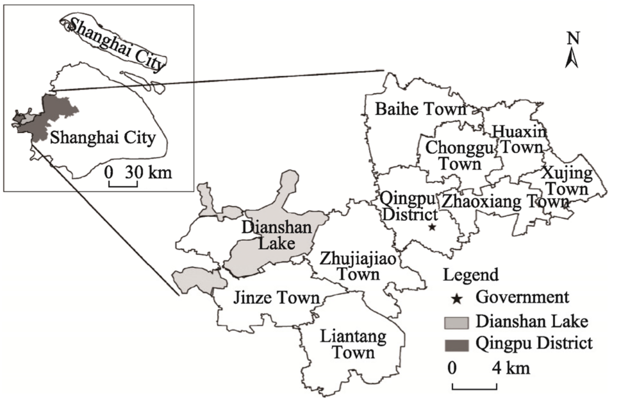

Fig. 2 Location of the case study area

In the last 10 years, driven by rapid urbanization and industrialization, Qingpu District had experienced more economic, social and ecological problems, profoundly affecting the sustainable social-ecological development in this region. The main manifestations were as follows. 1) Rapid urban expansion and a large scale of non-agricultural population transfer. For example, between the year 2008 and 2018, the urbanization rate in this area had increased by 1.18% annually, the population grew by 2.24-fold, the average annual increase in household registration was 23200, the rural labor transfer of 557900 people and so on (NBSC, 2009; NBSC, 2019). 2) The sustained growth of the GDP, despite a significant decline in total output value of agriculture. The total GDP increased from 57.429 billion yuan in 2008 to 83.957 billion yuan in 2018, an annual increase of 2.658 billion yuan, but the proportion of the agricultural industry fell 6.48% in the past 10 years (NBSC, 2009; NBSC, 2019). 3) Significant changes in land use types, and the scale of ecological land reductionwerelarge. Over the past 10 years, the total area of agricultural land had decreased by 701.96 ha, the area of water had decreased by 735.39 ha, and the area of construction land had increased by 795.84 ha, and so on (Ren et al., 2019; NBSC, 2009; NBSC, 2019). 4) The structure of land use was fragmentized and the diversity of the rural landscape was reduced. Under the double pressures of population surge and agricultural landscape area reduction, the average land patch density increased by 2.01, patch agglomeration decreased by 1.01 and the landscape diversity index decreased by 0.26 annually (Ren et al., 2019).

3.2 Methods

The basic research process in this study followed four steps. 1) Construction of a SEE-PSR model for the vulnerability efficiency evaluation index system based on the analysis of the definition and characterization of regional social-ecosystem vulnerability. CCR-DEA, ACE-DEA and EW-DEA efficiency evaluation models were used to evaluate and compare 184 administrative villages in Qingpu District. 2) Eleven geographical factors were selected from the natural and economic geographical dimensions. Meanwhile, the influences of geographical factors on the vulnerability of different regions and subsystems were analyzed using a geographical detection model. 3) The Q clustering method of hierarchical clustering analysis was used to divide the regional types. 4) In order to reveal the mechanism of regional social-ecosystem vulnerability, policy recommendations for regional ecological restoration and protection were presented according to the geographical type of vulnerability. These recommendations can reduce the vulnerability of social-ecosystems in conflict regions with 'strict protection and rapid development'.

3.2.1 Construction and verification of the vulnerability evaluation index system

(1) Evaluation indicator system for social-ecosystem vulnerability. As a complex and open system, the dissipation structure of the rural social-ecosystem produces internal and external energy and information exchange driven by the potential energy difference, which can be regarded as an 'input-output' system in essence (Ren et al., 2017). Social-ecosystem vulnerability is a conceptualized set of elements composed of exposure, sensitivity and adaptability, which are exposed to disturbances or external pressures, and have characteristics of sensitivity to disturbance and adaptability. It is a comprehensive embodiment of social system vulnerability, economic system vulnerability and ecosystem vulnerability (Adger et al., 1999). Due to its openness, and the comprehensive and dependent characteristics of the rural social-ecological system, the system was highly exposed and sensitive (Wang et al., 2015). The social-ecosystem has high sensitivity and low resistance to environmental disturbance, which led the system to change its original system structure, state and its functional attributes under the disturbance of the environment, showing a fluctuating and unstable state (Cannon et al., 2010). Among them, environmental disturbance plays a role in amplifying or reducing the vulnerability of the social-ecosystem and is also the decisive factor in the formation of vulnerability of the system (Pelling et al., 2005). However, the social-ecosystem can enhance the stability of the system through the self-organizing optimization of its own structure or the adjustment of human activity measures to achieve the stability of the system. From the above analysis, we can propose the analytical framework of PSR for the process of social-ecosystem vulnerability. Therefore, the 'SEE-PSR' models and multi-factor 'input-output' rural social-ecosystem vulnerability evaluation index system were constructed according to the definition and formation mechanism of vulnerability. Based on the SEE-PSR model, nine input factors for characterizing the pressures were selected from the three aspects of economy, society and environment. Twenty output factors from two aspects, that is, the state of the social-ecological subsystem and the response of each subject, were selected to characterize the state results and comprehensive coping abilities of the rural social-ecosystem vulnerability under these pressures (Table 1).

Table 1 Evaluation index system of social-ecosystem vulnerability in each administrative village in 2018

Target	Criteria	Indicator	Indicator description and data source
Economic vulnerability	Pressure (Input)	Gross income of region (yuan)	The overall regional economic difference, using economic statistics data
		Growth rate of secondary and tertiary industries (%)	The non-agriculture development difference, using economic statistics data
		Total value of farm output (yuan)	The agriculture development difference, using rural statistics data
	State (Output)	Per capita income (yuan person^{-1})	Individual resistance to vulnerability, using the household survey data
		Household income (yuan)	Family resilience to vulnerability, using the household survey data
		Net household income (yuan)	Family resilience to vulnerability, using the household survey data
	Response (Output)	Per capita disposable income (yuan person^{-1})	Family environment improvement capacity, using economic statistics data
		Road density (%)	Rural external communication capacity, using the land use vector data
Social vulnerability	Pressure (Input)	Urbanization rate (%)	Regional non-agricultural population pressure, using economic statistics data
		Total population (person)	Regional population carrying pressure, using economic statistics data
		Density of population (person km^{-2})	The per unit area population carrying pressure, using economic statistics data
	State (Output)	Net population outflow (person)	State of social identity change, using the rural survey data
		Ratio of settled and farmland (%)	State ofhousehold livelihood capital, using the land use vector data
		Number of agricultural workers (person)	Rural social employment, using the rural survey data
		Deserted farmland area (ha)	State of agricultural behavior, using rural statistics data
		Grain yield (t)	State of regional food security, using economic statistics data
	Response (Output)	Fixed investments (yuan)	Resilience in social services, using economic statistics data
		Household education expenditure (yuan)	Family resilience to vulnerability, using the household survey data
		Medical insurance coverage (%)	Resilience in public services, using economic statistics data
Ecological vulnerability	Pressure (Input)	Fertilizer usage (t)	Environmental pollution pressure of agriculture, using the rural survey data
		Plastic film application (t)	Environmental pollution pressure of agriculture, using the rural survey data
		Pollution emissions (t)	Industrial pollution pressure, using the environmental survey data
	State (Output)	Vegetation coverage (%)	State of green land, using the land use vector data
		Land degradation index	State of regional land quality, using the land degradation classification data
		Land patch density (piece ha^{-1})	State of land fragmentation, using the land use vector data
		Agricultural landscape fractal dimension	State of agricultural shape, using the land use vector data
	Response (Output)	Land consolidation area (ha)	Regional ecological improvement, using economic statistics data
		Environmental protection input (yuan)	Regional environmental protection efforts, using economic statistics data
		Grain production per unit area (kg ha^{-1})	Regionalfood productivity, using economic statistics data

(2) Evaluation indicator validation. The Data Envelope Analysis model (DEA) needs to satisfy the assumption of the expansion of input and output indexes. Accordingly, in order to overcome the limitation of the number of evaluation indexes in the decision-making unit and ensure the dominance and effectiveness of the efficiency evaluation model, the pre-construction input and output indexes were tested by Pearson correlation analysis, and the negatively correlated indexes were eliminated (Li et al., 2018). The results showed that both the input and output indexes were positively correlated, which satisfied the assumption of expansion of the DEA model. However, there were no significant correlations for the net population outflow and the medical insurance coverage, which should be well eliminated in principle. Considering that Qingpu District is an urban suburb, these two indicators reflected the rural characteristic state and the comprehensive coping abilities of the vulnerability, so the two indicators were retained.

3.2.2 Methods for vulnerability evaluation

The DEA model was used to evaluate rural social-ecosystem vulnerability. This method evaluated whether the decision-making units (DMU) with multiple inputs and outputs were located on the front surface of the production, and then determined their DEA validity. It is a classical model for evaluating the input-output efficiency of the system and has been widely used in the fields of operational research, management science, mathematical economics and so on (Wang et al., 2013). Owing to the diversity of available DEA models and their inherent shortcomings, three DEA models were used to evaluate and compare the vulnerability of the rural social-ecosystems. Since the extreme weight distribution of the CCR-DEA (Charnes-Cooper DEA) model led to the deliberate fragmentation of the correlation between evaluation units and difficulty in sorting vulnerability caused by the size (He et al., 2016) of the indistinguishable effective units, the CCR-DEA model was modified and compared with the ACE-DEA (Aggressive Cross Evaluation DEA). To overcome the problem that the optimal solution of the ACE-DEA model was calculated according to the principle of 'keeping the higher value, reducing the lower value', the evaluation result caused by the high correlation of the evaluation unit is too large, and the EW-DEA (Entropy Weight DEA) was constructed to improve the ACE-DEA model.

(1) The CCR-DEA model. Suppose, there are n DMU, m input samples and s output samples. Meanwhile, noting $x_{ij}$is the j-th sample of the i-th input factor and the r-th output factor. The k-th DMU_k is the evaluation unit. The equation of the CCR-DEA Model for DMU_k is as follows:

$$\begin{cases} E_{kk} = \max \sum_{r=1}^{s} \mu_{rk} y_{rk} \\ \text{s.t.} \quad \sum_{i=1}^{m} v_{ki} x_{ki} = 1 \\ \quad \sum_{r=1}^{s} \mu_{rk} y_{rk} - \sum_{i=1}^{m} v_{ki} x_{ki} \leqslant 0, \mu_{rk} \geqslant 0, v_{ki} \geqslant 0 \end{cases} \quad (1)$$

where E_{kk} is the vulnerability efficiency of the k-th DMU; v_{ki} and u_{rk} are the related weight coefficients; and x_{ki} and y_{rk} are the values of the different DMUs. Equation (1) was solved n times and the self-evaluation efficiency value of n DMU was obtained. The DMU was valid when the efficiency value was 1; otherwise, the DMU was invalid.

(2) The ACE-DEA model. To overcome the problem that the CCR-DEA model based on self-evaluation efficiency cannot distinguish the vulnerability ranking of multiple effective DMUs at the same time, the ACE-DEA model based on other evaluation efficiencies was adopted on the basis of relevant research. The principle of the model is to use the CCR-DEA model to calculate each E_{kk} value, under the premise of ensuring the maximum E_{kk} of the evaluation unit, and making the cross-evaluation value ofE_{ki} as small as possible in the other DMUs. The equation is as follows:

$$\begin{cases} \min \sum_{r=1}^{s} \mu_{rk} y_{rk} \\ \text{s.t.} \quad \mu_{rk} y_{rk} \leqslant v_{ki} x_{ki}, \sum_{i=1}^{m} v_{ki} x_{ki} = 1, \mu_{rk} \geqslant 0, v_{ki} \geqslant 0 \\ E_{ki} = \dfrac{\sum_{r=1}^{s} \mu_{rk} y_{rk}}{\sum_{i=1}^{m} v_{ki} x_{ki}} \end{cases} \quad (2)$$

where E_{ki} is the efficiency value of the i-th DMU calculated using the optimal weight of the k-th unit;v_{ki} and u_{rk} are the related weight coefficients; and x_{ki} and y_{rk} are the values of the different DMUs.

(3) The EW-DEA model. A distance entropy model was introduced to improve the ACE-DEA model in order to overcome the high evaluation result caused by high correlation (Sexton et al., 1986). Entropy is a measure of system uncertainty and positively correlated. The entropy value of the h_{ki} is an attribute of the k-th for the i-th DMU. The equation is as follows:

$$h_{ki} = -\left(E_{ki} / \sum_{k=1}^{n} E_{ki} \right) \times \ln \left(E_{ki} / \sum_{k=1}^{n} E_{ki} \right) \quad (3)$$

By introducing the concept of distance entropy, the equation of the distance entropy is as follows:

$$d_{ki} = \left| h_{ki} - h_{kk} \right|, k = 1, 2, \cdots, n \quad (4)$$

where d_{ki} is the distance entropy of the k-th DMU_k, h_{ki} is the cross efficiency and h_{kk} is self-cross efficiency of the DMU_k.

The practical significance of distance entropy is that the smaller the value, the smaller the uncertainty between self-evaluation and other evaluation, that is, the better the consistency and the greater the weight of assembly. The assembly weight of the γ_{ki} is as follows:

$$\gamma_{ki} = \frac{\left| d_{ki} \right|}{\sum_{k=1, i \neq k}^{n} \left| d_{ki} \right|} \quad (5)$$

The ultimate rural vulnerability efficiency was determined by a linear weighting method. The equation is as follows:

$$E_k^* = \theta E_{kk} + (1 - \theta) \sum_{k=1, i \neq k}^{n} \gamma_{ki} E_{ki} \quad (6)$$

where E_k^* is the integrated vulnerability efficiency of the k-th DMU; E_{ki} is the efficiency value of the i-th DMU; E_{kk} is the vulnerability efficiency of the k-th DMU; γ_{ki} is the assembly weight; and θ is the evaluation coefficient and its value is in [0,1]. According to Li et al. (2018), the value was 0.5.

3.2.3 Validation method for vulnerability evaluation

To verify the high evaluation results of the ACE-DEA model due to association, the spatial autocorrelation analysis method of GeoDa095 software was used to analyze the spatial agglomeration characteristics of vulnerability. The detailed research process is shown in a previous publication (Ren et al., 2019).

3.2.4 Geographical influencing analysis

(1) Geographic detector method. Based on the theory of spatial differentiation and set theory, geographical detector models are widely used in the study of spatial relationships, pattern evolution and regional spatial differentiation of geographical factors by using the technique of spatial superposition to identify the interactive causality between multiple factors (Wang et al., 2012). Geographical detector models

were used to analyze the influence of factors (Q_v) on the spatial differentiation of the rural social-ecosystem vulnerability. Different village-based $RV_{S\text{-}E}$ (rural social-ecosystem vulnerability values) are randomly distributed in the study area, resulting in a lattice system. Suppose that A_i was the geographical factor that affected the $RV_{S\text{-}E}$. To detect the spatial correlation between A_i and $RV_{S\text{-}E}$, the two layers were superimposed and the discrete variance of the $RV_{S\text{-}E}$ was analyzed, so as to judge the causality of the two factors. The equation is as follows:

$$Q_v = 1 - \frac{1}{n\sigma^2}\sum_{h=1}^{l} n_h \sigma_h^2 \quad (7)$$

where n_h is the number of samples included in the type h in the factor A_i; n is the total number of samples in the region; l is the number of classifications for A_i; σ^2 is the discrete variance for the study area; and σ_h^2 is the variance of dispersion in the sub-regions. If $\sigma_h^2 \neq 0$, the model may be established and the range of Q_v is [0,1]. If Q_v=0, there may be a random distribution in the region. The greater the Q_v, the greater the impact of A_i on $RV_{S\text{-}E}$. By comparing the influence Q_v of geographical factors, this method analyzed the leading factors of regional differentiation of social-ecological system vulnerability in the administrative villages.

(2) Geographical variable selection. Geospatial factors rooted in regional endowment conditions have an important impact on regional social-ecosystem vulnerability (Lu et al., 2019). The analysis of spatial variation of vulnerability based on these elements can give a better perspective on the law and mechanism of the spatial differentiation of vulnerability and provide the basis for improving regional geographical conditions. Therefore, 11 indexes were selected to characterize the natural and economic attributes of geographical factors (Table 2).

Table 2 Geographical factors influencing social-ecosystem vulnerability of the administrative villages

Category	Indicator	Calculation method
Natural Geographical Attributes	Y_1 Slope (%)	Slope data (resolution 30 m). Using DEM data extraction and re-classification: 0°–1°, 1°–2° and 2°–3° assigned to 1, 2, 3
	Y_2 Elevation (m)	Elevation data (resolution 30 m). Using DEM data extraction
	Y_3 Agricultural acreage (ha)	Extraction of arable land areas from land vector maps
	Y_4 Water area (ha)	Extraction of water areas from land vector maps
	Y_5 Distance from nearest river (km)	Using the river grid data extraction statistics. Grid vector layer (30 m*30 m), overlay administrative village committee and river grid layer, and use grid calculator statistics
	Y_6 Distance from Dianshan Lake (km)	The calculation process was the same as above (Y_5). Statistics from Village Committee to Dianshan Lake Center
Economic Geographical Attributes	Y_7 Distance from nearest main road (km)	The calculation process was the same as above (Y_5). Statistics from Village Committee to the nearest main road
	Y_8 Distance from township center (km)	The calculation process was the same as above (Y_5). Statistics from Village Committee to the nearest township center
	Y_9 Distance from center of Qingpu District (km)	The calculation process was the same as above (Y_5). Statistics from Village Committee to the Government of Qingpu District
	Y_{10} Distance from center of Shanghai City (km)	The calculation process was the same as above (Y_5). Statistics from Village Committee to the Government of Shanghai City
	Y_{11} Space accessibility among village	The 'grid calculator' was used to calculate the minimum time cost of each grid after the superposition of the road grid layer and the ground grid layer The average value of all time costs associated with an administrative village were used as the index value of spatial accessibility of the village area

3.3 Data sources and processing

3.3.1 Data sources

Geospatial Data. The geospatial data originated mainly from the 1:5000 maps for the LULC in the year 2018, which were provided by the Qingpu District Land Bureau. Spatial data on rivers, roads, water systems and townships were extracted from basic geographic databases. The DEM data source was CAS Computer Network Information Center International Scientific Data Mirroring Website data period (http://datamirrior.csdb.cn) and the data were reclassified for the extraction of slope and elevation data.

Social-economic Statistics Data. The social-economic statistical data were collected from the China Statistical Yearbook (2009, 2019), the China City Statistical Yearbook (2009, 2019), the Shanghai Statistical Yearbook (2009, 2019), the Qingpu Statistical Yearbook (2009, 2019), and the past editions of the Land & Resource Bulletin and the Water Conservancy Annals of Shanghai. The social-economic data on the village scale were obtained from the Qingpu Statistical Bureau and the Qingpu Agriculture Committee.

Household Survey Data. Village land data were obtained from the 'Rural Collective Construction Land Reduction Census' in the year 2019. The social and economic data of farmers were derived from the data of farmers at the fixed observation points in rural areas of the Agricultural Commission and the participatory peasant household survey carried out by five people in the research group from July to

October 2019 (with a total of 1485 copies, the effective recovery rate was 95%). The questionnaire consisted of nine parts: the composition of family members, the land situation, the fixed assets situation, the household production and operation situation, the sale of agricultural products, the purchase of the means of production of the planting industry, and so on. Cronbach's alpha coefficient method was used to test the reliability of survey data. The overall Cronbach's alpha coefficient of the survey sample index was 0.895, which indicated that the survey data were reliable.

3.3.2 Data processing

The data processing method was as follows. As referenced by the Technical Regulation (TD/1014-2007) of the Second National Land Survey, land cover in this study was classified into eight classes by considering local expert knowledge: forest, grassland, water bodies, arable land, garden, transport land, unused land and built-up area. In order to calculate the idle land plaques, landscape dimensionality, and land patch density, the land-cover maps of Qingpu District were transformed to a pixel size of 30 m×30 m, then the soft Fragstats3.3 was used for the calculation and spatial statistics on ArcGIS in order to calculate the road density. According to the *Technical Standard of Transportation Engineering* (JTGB01-2003) of the People's Republic of China, the time costs of different types were set. With the help of the grid calculator tool, the minimum time cost of each grid after the superposition of the road grid layer and the ground grid layer was obtained, and superimposed with the village committee data. Construction of the spatial accessibility network between villages was carried out with Graphab software. Based on the derived shape file, the time cost distance between any two villages was determined, and the mean value of all the time costs associated with the administrative village was used as the index value of the spatial accessibility of the rural area.

4 Results and interpretations

4.1 Results of social-ecosystem vulnerability evaluation for different models

(1) Regional differentiation. According to the evaluation results of the vulnerability (RV_{S-E}) of 184 administrative villages in Qingpu District (Table 3), the spatial difference of the RV_{S-E} was significant. The range of the RV_{S-E} values of the EW-DEA model was [0.404, 0.787], and the minimum administrative village value was that of Hengjiang Village (0.404). The range of RV_{S-E} for the ACE-DEA model was [0.433, 0.812], and the minimum value was for Xiaojiang Village in Zhujiajiao (0.433). However, the range of the RV_{S-E} values of the CCR-DEA model was [0.421, 1.000], and the maximum value among the administrative villages was 16.

The averages of RV_{S-E} for the different models were as follows: 0.699 (ACE-DEA model)>0.623 (CCR-DEA model) > 0.583 (EW-DEA model). The average of RV_{S-E} for the different regions were as follows. The maximum RV_{S-E} was in the east of Qingpu District (ACE-DEA model), yet the minimum RV_{S-E} was the value for the EW-DEA model. The minimum RV_{S-E} was the value of the EW-DEA model (0.609) in the west region, yet the minimum RV_{S-E} was the value of the EW-DEA model (0.554) in the center.

Table 3 The comparison of vulnerability assessment for administrative villages in Qingpu District of 2018

Region	CCR-DEA model		ACE-DEA model		EW-DEA model	
	Average of RV_{S-E}	RV_{S-E}	Average of RV_{S-E}	RV_{S-E}	Average of RV_{S-E}	RV_{S-E}
Qingpu District	0.623		0.699		0.583	
Eastern part	0.689		0.756		0.625	
Central part	0.542		0.643		0.554	
Western part	0.638		0.699		0.609	
Guanglian Village in Xujing		0.598		0.665		0.662
Songshan Village in Huaxin		7.125		7.193		7.194
Chuiyao Village in Zhaoxiang		0.629		0.698		0.703
Zhongxin Village in Chonggu		1.000		0.924		0.648
Tangyu Village in Xiayang		0.554		0.655		0.592
Heqiao Village in Yingpu		0.665		0.777		0.706
Jinxing Village in Xianghuaqiao		1.000		0.964		0.614
Wangjing Village in Baihe		1.000		0.972		0.729
Wanlong Village in Zhujiajiao		0.551		0.632		0.580
Beidai Village in Liantang		1.000		0.985		0.732
Tianshanzhuag Village in Jinze		0.582		0.676		0.626

According to the $RV_{S\text{-}E}$ of the villages, the vulnerability of each administrative village in Qingpu District varied markedly in the three models. The differences of each model were compared among 11 administrative villages (Table 3). The differences in the $RV_{S\text{-}E}$ for administrative villages in the three models were significant. Among them, the values of the ACE-DEA model were significantly higher than those of the other two models. The $RV_{S\text{-}E}$ values of the CCR-DEA and EW-DEA models were close. However, the CCR-DEA model results were divided into two types: effective units ($RV_{S\text{-}E}$ =1) and non-effective units ($RV_{S\text{-}E} \neq 1$), and the results cannot distinguish the effective units (Zhongxin Village, Jinxing Village, Beidai Village, etc.) from each other.

(2) Differentiations of spatial agglomeration. In order to verify the high evaluation results of the ACE-DEA model due to association, the following results were obtained by a spatial autocorrelation analysis of the $RV_{S\text{-}E}$ from the three models. At a 5% significance level, the Z values of the EW-DEA, ACE-DEA and CCR-DEA models were 6.998, 17.558 and 10.254, respectively. All three results were above the critical value of 1.96, passing the significance test. However, the Moran's I values of the three models were as follows: ACE-DEA (0.815) > EW-DEA (0.384) > CCR-DEA (0.248), indicating that the spatial correlation of $RV_{S\text{-}E}$ under the ACE-DEA model was obviously higher than under the other two models. This result objectively validated the conclusion of He et al. (2016) and Li et al. (2018) regarding the differences of spatial correlation caused by the evaluation results which were on the high side for the ACE-DEA model. Meanwhile, it provided a basis for rejecting the evaluation results of the ACE-DEA model in this study.

4.2 Results of social-ecosystem vulnerability evaluation for EW-DEA model

4.2.1 Results of sub-social-ecosystem vulnerability evaluation

The average $RV_{S\text{-}E}$ values of the social, economic and economic subsystems in Qingpu District in 2018 were: social system (0.612) > economic system (0.589) > ecological system (0.548). The vulnerability of the social systems was an important factor limiting the vulnerability of the region.

(1) The vulnerability of social systems increased from the center to the eastern-western portions (Fig. 3a). The central region had become the low value region of social vulnerability because of the balanced pressure, the large investment and wide coverage of regional public services and other factors. Specifically, this region had the largest number of employees, road density, household education expenditure and medical insurance coverage, which were higher than the regional averages of 25.33%, 35.57%, 54.24% and 29.57%, respectively. The greatest vulnerability in the eastern region was due to the relatively low response capacity of society due to excessive environmental pressures in the region.

(2) The vulnerability of the economic system increased in the northern and southern parts along the central axis of the region, that is, spatially Xujing-Zhaoxiang-Xiayang-Zhujiajiao (Fig. 3b). The special economic location of the double economic center in this area had become an important factor for resisting economic vulnerability. Specifically, the eastern region had greatly enhanced the per capita income and industrial value-added capacity in undertaking industrial transfer in Shanghai. Under the rapid development of its own economy, the central region had strong abilities to resist vulnerability. However, the western region adjacent to Dianshan Lake area was also strong in developing its tourism industry and enhancing economic development. On the contrary, in the northern region and the southern region far away from the economic radiation area, the traditional planting industries were the main economic pillars. Although the above areas had taken some measures to control the pollution emissions of the agricultural industry, the economic growth capacity of the area was limited and the economic vulnerability was high.

(3) Ecological vulnerability increased from west to east in the Qingpu District (Fig. 3c). The system vulnerability in this area showed an obvious secondary differentiation, that is, the $RV_{S\text{-}E}$ values (0.453) of the western region located around Dianshan Lake were very low, while those of the eastern region (0.731) far away from Dianshan Lake were high. The main reason for the pattern of secondary differentiation was the limitation of multiple planning. Specifically,

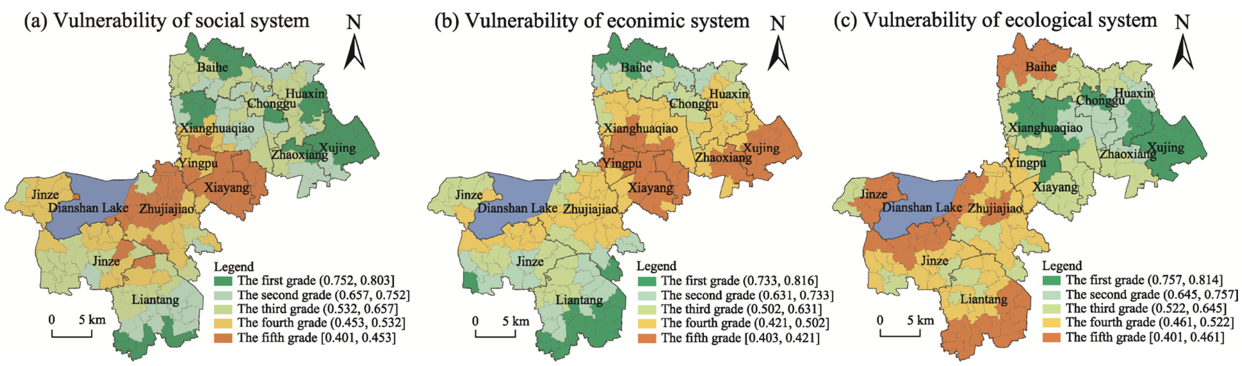

Fig. 3 Social-economic-ecosystem vulnerability in Qingpu District in the year 2018

under the restriction of water conservation planning, the western region strictly limited the degree of development and the threshold of industrial entry. At the same time, the regional consolidation projects vigorously promoted the low ecological vulnerability. Yet under the pressure of rapid economic development, the ecological vulnerability in the eastern part was high.

4.2.2 Grades of social-ecosystem vulnerability at village scale

To analyze the spatial distribution of the factors influencing social-ecosystem vulnerability, the natural breakpoint method of ArcGIS was used to divide the $RV_{S\text{-}E}$ of the 184 administrative villages in Qingpu District in the year 2018. The results are shown in Fig. 4.

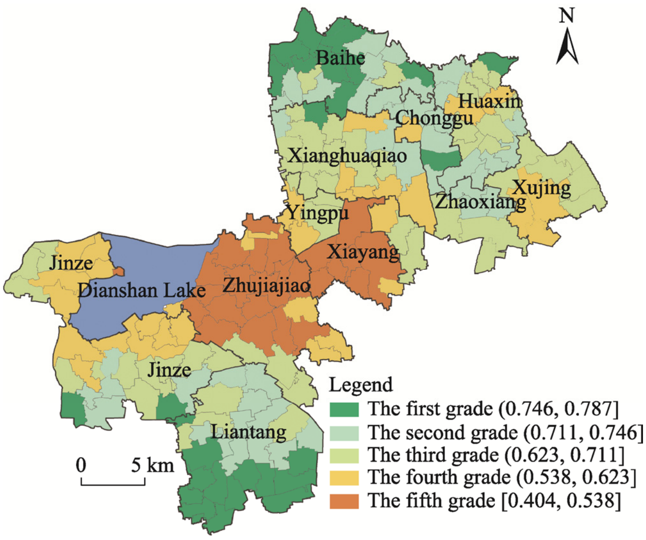

Fig. 4 Social-ecosystem vulnerability grades in Qingpu District in 2018

Based on the results of natural breakpoints for $RV_{S\text{-}E}$, the 184 villages can be divided into five grades, and spatial performance from the central area to the north-south show incremental changes. The number and area of the administrative villages with moderate vulnerability (the third grade) in Qingpu District were the largest, that is, 49 and 153.43 km^2, respectively. In that grade, the village $RV_{S\text{-}E}$ values ranged from 0.623 to 0.711, mainly distributed in the central and eastern parts, specifically, in Xujing, Yingpu, Zhaoxiang, Xianghuaqiao and others. The area of high vulnerability (the first grade) was 121.12 km^2, which accounted for 18.14% of the total area of the region, mainly in the southern and northern parts of the district, specifically, primarily in Liantang and Baihe. The administrative villages with low vulnerability (including the fourth and fifth grades) were concentrated in the central and western parts, specifically, in Xiayang, Zhujiajiao, Jinze and others. The $RV_{S\text{-}E}$ in these two grades ranged from 0.404 to 0.623, and included 75 administrative villages, which accounted for 40.76% of the total villages.

4.3 Impact of geographic factors on spatial differentiation

4.3.1 Survey of geographical factors

In order to identify the geographical factors that affected the spatial differentiation of social-ecosystem vulnerability, 11 geographical indexes selected from the two dimensions of natural and economic attributes were tested (Table 4). Since the Slope factor is a multi-classification variable, the Binary Logistic module of a multivariate Logistic regression model was used to analyze the regression coefficient and the variance expansion factor of multivariate collinearity. The regression results showed that the factors of Y_9 (Distance from Shanghai Center, 0.452), Y_6 (Distance from the Dianshan Lake, 0.401), Y_{10} (Distance from center of Shanghai City, 0.388), Y_4 (Water area, 0.374), Y_{11} (Space accessibility among village, 0.367), Y_7 (Distance from nearest main road, 0.324) and Y_3 (Agricultural acreage, 0.283) were significant and positively correlated at the 0.01 level. The variance expansion factors of the other four factors were more than 15, indicating a severe collinearity, so they were eliminated.

Table 4 The coupling results of vulnerability grades and influencing factors

Matching type	Y_9	Y_6	Y_{10}	Y_4	Y_{11}	Y_7	Y_3
–4	6.63	10.25	8.68	4.55	0.85	5.66	1.67
–3	15.57	19.54	16.52	16.68	9.66	12.68	10.57
–2	29.68	28.54	25.35	22.58	18.57	19.54	16.68
–1	37.51	35.44	29.87	26.64	26.64	24.65	19.54
0	43.56	41.25	34.89	33.45	32.24	31.55	25.67
1	8.51	9.56	5.65	5.65	3.55	2.51	3.24
2	19.65	18.64	16.66	14.68	16.54	14.66	15.63
3	34.57	25.62	26.58	26.44	27.66	22.28	21.58
4	49.68	34.58	40.11	39.54	41.42	37.65	32.54

Note: Variable names are given in Table 2.

4.3.2 Influence of the dominant geographical factors

In order to analyze the influences of geographical factors on the vulnerability of different regions and subsystems, the geographical detector model for multilevel detection yielded the following three main results (Table 5).

(1) Significant spatial differentiation in the influence of the dominant geographical factors. Table 5 shows that the influence of the four dominant factors which affected the vulnerability of the social-ecosystem in Qingpu District were: Distance from center of Shanghai City (Y_{10}), distance from Dianshan Lake (Y_6), distance from the center of Qingpu District (Y_9), and water area (Y_4).

As an important indicator of economic location, the distance from the center of Shanghai City reflected the difficulty in receiving economic radiation in the region, which was inversely proportional to the geographical distance. Qingpu District, which is close to the core area of Shanghai

City, has the function of undertaking urban industry and population transfer. Through the inflow of new industrial production modes, high quality industrial workers and an urbanized way of life, economic vulnerability had been overcome to some extent. However, its radiation ability was also weakened with the increase of distance, which led to the spatial trend of the index's influence.

As an important index for characterizing geographical location, the distance from Dianshan Lake reflected the degree of radiation from special geographical resources, which was inversely proportional to geographical distance. As a water conservation site in Shanghai City, Dianshan Lake has its unique geographical resources, which greatly restricted the utilization and development of the resources in its area, in order to maintain the integrity of the ecosystem and ensure the function of water conservation. The above reasons became an important factor in resisting ecological vulnerability. However, under the radiation attenuation of planning principles and indicators of zoning control, the influences of this area decreased from the western to the eastern parts.

Table 5 Coupling analysis of vulnerability grades and influencing factors

Region	Township	Y_6	Y_7	Y_3	Y_{11}	Y_9	Y_4	Y_{10}
Eastern part	Xujing	0.446	0.269	0.115	0.329	0.584	0.326	0.358
	Zhaoxiang	0.459	0.258	0.126	0.308	0.572	0.338	0.369
	Huaxin	0.449	0.246	0.175	0.215	0.569	0.345	0.372
	Chonggu	0.455	0.281	0.205	0.229	0.557	0.366	0.395
	Baihe	0.385	0.314	0.459	0.217	0.507	0.397	0.337
Central part	Xiayang	0.315	0.210	0.511	0.262	0.451	0.401	0.468
	Xianghuaqiao	0.324	0.235	0.469	0.259	0.449	0.386	0.459
	Yingpu	0.339	0.219	0.485	0.253	0.432	0.412	0.447
Western part	Zhujiajiao	0.512	0.345	0.411	0.401	0.495	0.450	0.455
	Liantang	0.499	0.348	0.109	0.354	0.502	0.259	0.451
	Jinze	0.642	0.195	0.516	0.358	0.265	0.491	0.311
Qingpu District		0.475	0.304	0.284	0.331	0.532	0.394	0.428

Note: Variable names are given in Table 2.

The distance from the center of Qingpu District reflected the difficulty or ease in receiving radiation from the local economy and public services, which was inversely proportional to geographical distance. Qingpu District center has well-developed education, medical care, social security, social services, and financial services, which had an important impact on regional social-ecosystem vulnerability. The closer to the district center, the easier access to convenient infrastructure and social and economic development brought about by inclusive policies; but, conversely, the less regional capacity to receive public services. Under the influence of distance, the influence of this indicator showed the spatial pattern of high in the central parts and low in the surrounding parts.

As an important indicator of resource endowment, water resources are the material basis of regional development and proportional to resource abundance. Qingpu District is a plain water network region with abundant river and water resources. The abundance of water resources has an important influence on regional industrial transformation, improving the quality of regional development, changing the regional production and life style, and expanding the regional economic links. This indicator had a strong impact on regional social-ecosystem vulnerability. Under the influence of water resource abundance, the influence of this indicator showed the spatial pattern of high in the western parts and low in the eastern parts.

(2) The influence of geographical factors showed the characteristics of substitution and degree transformation, and the influences of economic geographical indicators were greater than the natural geographical indicators. The analysis of seven dominant geographical indicators (Table 5) and the economic geographical indicators (Y_{10}, Y_9, Y_7 and Y_{11}) in Qingpu District indicated that they were higher in quantity and degree than those of the natural geography indicators, so they had more profound impacts on the vulnerability of social-ecological systems in this region. The above results showed that the economic geographical elements coupled with human response behaviors and spatial nature had more externalities than the purely natural elements. This kind of geographical index relied on the human behaviors such as economic expansion, social transformation and environmental disturbance to impact the regional social-ecological system quickly, which first led to the change of the system structure and functions, and then affected the vulnerability of the social-ecosystem. In contrast, the influence of natural geographical elements on the system is more manifested as background environmental factors, with recessive and slow characteristics.

The results of structural analysis showed that the influence of water area (which characterized regional resource endowment) was higher than that of agricultural acreage; and the indicator of spatial accessibility among villages was higher than that of Distance from nearest main road. These results were different from those of Wang et al. (2015), Li et al. (2015) and Chen et al. (2015). Regional differences may be an important reason for the differentiation seen in the above results. As a water conservation region in the suburbs of Shanghai City, the resource endowment index of Qingpu District, which affected the vulnerability of the social-ecosystem, had changed from a resource attribute to an asset attribute under the influences of economy and regional demand. The functions of resources had changed from the agricultural production function to the economic development function and aesthetic enjoyment function. At the same time, the industrial types and production structure of the region were constantly changing in the process of accepting the economic radiation of Shanghai City. 'Hardware-traffic factor-indirect connection' was a means of linking regional economic development in the past, but its influence on the correlation degree of the vulnerability was weakened. Instead, the 'software-industry chain acceptance and complementary accessibility factors-direct connection' model has become the new way.

(3) The influence of geographical factors presented structural spatial differences, with the greatest impact on social subsystems. The following results were obtained by analyzing the impacts of geographical factors on the subsystem vulnerability of rural social-ecosystems (Table 6). From the spatial differentiation analysis of the influence of geographical factors on local subsystems, economic geographical factors had great influences on the ecological subsystem and social subsystem in the eastern parts. Among them, the distance from the center of Shanghai City had the greatest influence on the ecosystem (0.689), while the distance from the center of Qingpu District had the greatest influence on the social subsystem (0.438). However, the natural geographical factors had a great influence on the social system (0.454) and the economic system (0.421) of the western parts. From the whole region perspective, the average influences of geographical factors on subsystems were: social system (0.329), ecological system (0.319) and economic system (0.308), and the influences of economic geographical factors were higher than those of the natural geographical factors. The main reasons for these results were that the social system based on long-term social humanities and production and life style had stronger structural rigidity (Tai et al., 2006). When the social system faced changes driven by external pressure, it often adapted to environmental change by restructuring itself. This process produced a time lag (Tai et al., 2006), and it showed a strong hindrance. So that the environmental adaptabilities of the subsystem were relatively solidified, the response abilities of the subject of the system lagged behind and the system vulnerabilities were produced.

Table 6 The coupling analysis of vulnerability grades and influencing factors

Region	Subsystem	Y_6	Y_7	Y_3	Y_{11}	Y_9	Y_4	Y_{10}
Eastern part	Social system	0.387	0.259	0.188	0.169	0.511	0.115	0.438
	Economic system	0.212	0.208	0.109	0.161	0.586	0.074	0.354
	Ecological system	0.145	0.186	0.125	0.175	0.689	0.106	0.341
Central part	Social system	0.336	0.393	0.274	0.311	0.497	0.325	0.498
	Economic system	0.301	0.328	0.227	0.264	0.457	0.247	0.468
	Ecological system	0.299	0.337	0.241	0.301	0.448	0.295	0.457
Western part	Social system	0.454	0.232	0.438	0.194	0.396	0.428	0.404
	Economic system	0.421	0.228	0.425	0.148	0.336	0.417	0.333
	Ecological system	0.409	0.214	0.412	0.186	0.298	0.398	0.347
Qingpu District	Social system	0.396	0.279	0.267	0.235	0.435	0.279	0.413
	Economic system	0.365	0.255	0.254	0.191	0.460	0.246	0.385
	Ecological system	0.381	0.246	0.259	0.221	0.478	0.266	0.382

Note: Variable names are given in Table 2.

4.4 Spatial coupling patterns of geographical factors for social-ecosystem vulnerability

The geographical factors of regional social-ecosystem vulnerability exhibited regional adaptability and spatial agglomeration. It is of great significance to analyze the regional types of vulnerability as influenced by the mechanisms of geographical factors, and to adopt related local policies and differentiated regulatory measures to reduce the vulnerability of the regional social-ecosystem. Four dominant geographical factors were found to influence the social-ecosystem vulnerability of 184 administrative villages, and they were studied by hierarchical clustering analysis (Q clustering method) to divide them into regional types. According to the results of Q clustering, the following zoning methods were adopted: 1) The principle of maximum differentiation, the principle of hierarchical system, the principle of relative consistency and the principle of regional full coverage. 2) The most dominant factors were used to classify the multiply dominated geography without significant influence. 3) In addition, the distance between classes was 0.073.

The clustering results showed that the spatial types of geographical factors influencing social-ecological vulnerability in Qingpu District can be divided into 10 types, that is, four kinds of single factor types, three kinds of double factors types, two kinds of triple factors types and one kind of quadruple factor type (Fig. 5). The spatial coupling types of geographical factors influencing social-ecological vulnerability in Qingpu District were mainly influenced by multi-factor coupling. The spatial patterns of coupling types presented multiple circular features, dominated by multi-factor coupling in the middle and by single-factors around the region. Areas affected by single factors covered 210.60 km^2, mainly distributed along the perimeter of the Qingpu District, and including 55 administrative villages. Among them, economic and environmental intimidated type is the main type, accounting for 9.59% of the total area of the region. Multi-factor coupling affected 68.50% of the total area, mainly distributed in the central part and involving 129 administrative villages. Among them, the economic and natural environment coupling was the main influence type, which affected 12.44% of the total area, mainly distributed in the central and western parts. The economic environment-natural environment-public service compound influence type was the main triple factor coupling influence type, which affected 16.79% of the total area, and was mainly distributed in the middle, specifically, in Yingpu, Xiayang, Xianghuaqiao and Zhujiajiao. The 12 administrative villages

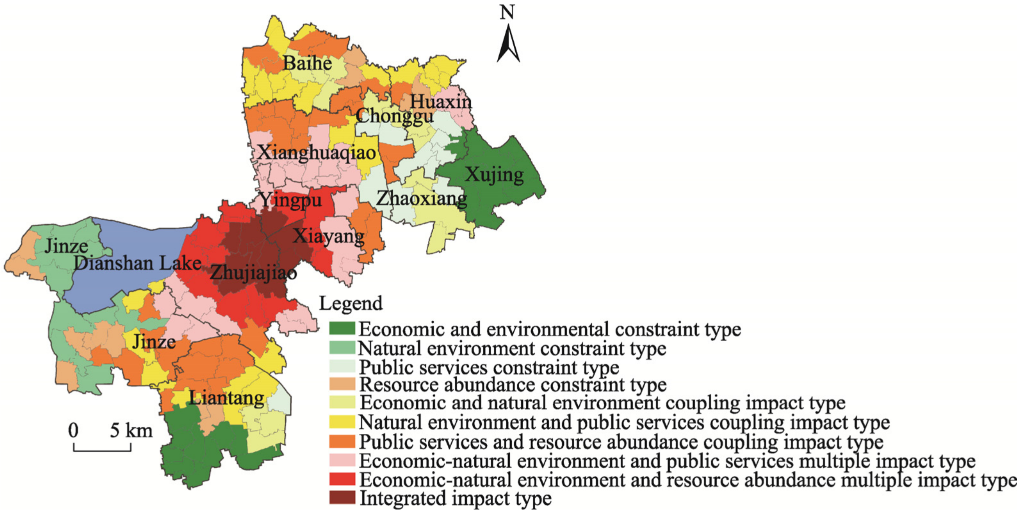

Fig. 5 The spatial distribution of coupling types of the geographical factors for social-ecosystem vulnerability in Qingpu District

with the comprehensive influence type of geographical factors were mainly distributed in Xiayang and Zhujiajiao in the central part.

According to the division of geographical factor spatial coupling models of social-ecosystem vulnerability in Qingpu District, the distributions of geographical factors and the regional social-ecosystem vulnerability had a high spatial overlap. Geographical factors still had an important impact on the social-ecosystem vulnerability in economically developed regions. However, the level and mode of the influence of those kinds of factors on the vulnerability of social-ecosystem in economically developed regions were very different from in poor regions. This was especially true in poor mountainous regions, where the vulnerability caused by a single factor was gradually weakened. Yet the vulnerability caused by compound multiple factors was obvious. On the one hand, the developed region had become an open system deviating from the equilibrium state under the rapid advancement of economic factors. With the transformation of the system, the single natural geographic factor had been internalized as the background factor of the change of social-ecosystem vulnerability. The independence of the influencing vulnerabilities had been diluted in the process of each subsystem element's flow and system fusion, and the attachment and transformation of various attributes even occurred. For example, the distance from Dianshan Lake was endowed with the economic and ecological attributes of regional industrial differentiation and regional ecological demand. The resource attributes of water had been replaced by economic assets and regional resource value-added attributes. On the other hand, with the continuous impact of social transformation, economic change, industrial replacement, and self-interest of human behaviors on this deviant equilibrium system, the abilities of economic geographical factors and multi-factor coupling factors to form vulnerability were more obvious. The formation process of this compound vulnerability was as follows: Relying on the diversity of economic industries to change the vulnerability of economic subsystems, relying on the urbanization of human customs to change the vulnerability of social subsystems, and relying on the diversity of human needs changes the vulnerability of ecological subsystems. At the same time, under the influence of the differences in the regional natural geographical location and the imbalance of the system structure, the regional patterns of regional social-ecosystem vulnerability differentiation had finally come into being (Fig. 6).

4.5 Policy implications

The results of the spatial coupling types of geographical factors not only clarified the coupling mechanism of the dominant factors of regional differentiation of social-ecological system vulnerability in different regions, but they also provide a relevant basis for the regional ecological restoration. In the new period, integrated territory consolidation is based on the regulation of the relationships between man and resources. By means of arrangement, development, restoration, management and protection, the activities of promoting human living and production conditions, preserving ecological space and finally promoting the sustainable and integrated development of man and nature can be achieved (Xia et al., 2018). Therefore, according to the different types, some feasible ways and policy suggestions of ecological restoration, which draw on the experience of integrated territory consolidation, are proposed to remediate the vulnerability of rural social-ecological systems (Table 7).

(1) Economic and environmental intimidation type. Relying on the influence of economic location, this kind of region presented an obvious polarization phenomenon (distributed in suburban villages). The vulnerability of the social subsystem presented a higher level under the rapid loss of the rural population of the suburban village, and the gov-

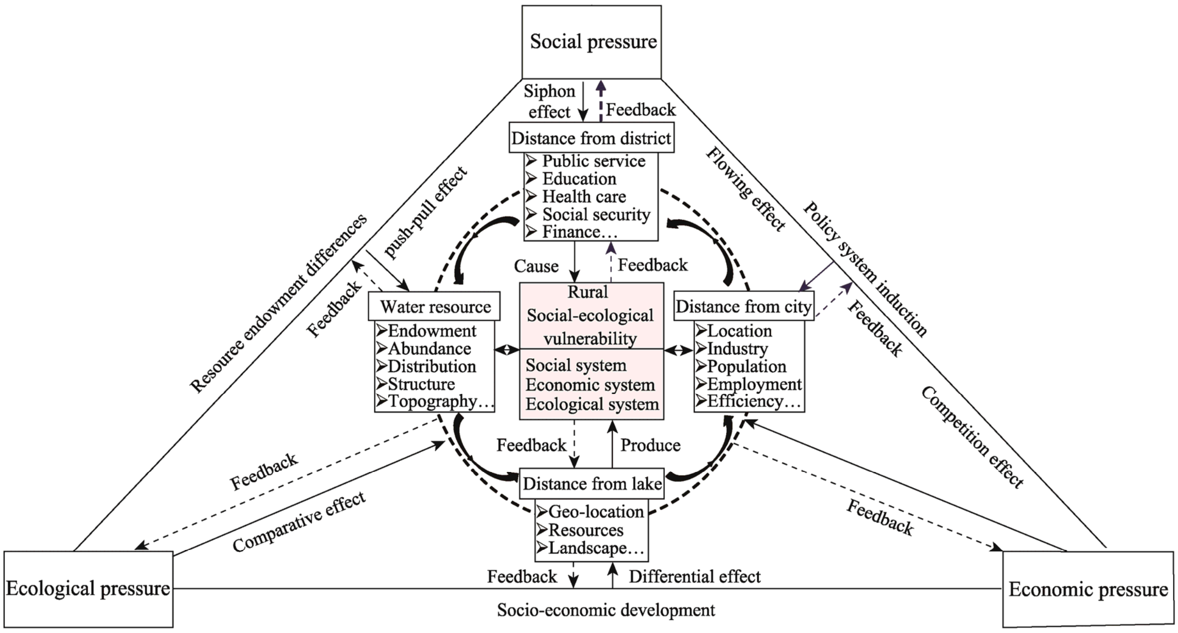

Fig. 6 The mechanism of geographical coupling for rural social-ecosystem vulnerability

Table 7 The geographical impact types and ecological restoration modes of the social-ecosystem vulnerability in Qingpu District

Geographical impact types	Vulnerability characteristics	Governance emphases	Governance measures	Governance objects	Restoration modes
Economic environment constraint type	High grade of vulnerability High vulnerability of social and ecological systems Rapid loss of the rural population and rural culture dies out	Rural organization and culture	Comprehensive rural social improvement	√ Rural subject raise √ Rural order reconstruction	Embedded mode
Natural environment constraint type	Low grade of vulnerability High vulnerability of economic system Agricultural productivity and environmental pollution	Land resources	Agricultural land renovation	√ Cultivated land protection, capacity upgrade √ Leisure industry exploited	Consolidation mode
Public services constraint type	High grade of vulnerability High vulnerability of social and ecological systems Unequal coverage of public services	Social public spaces	Removing and reforming government	√ Multi-subject coordination √ Step-by-step promotion	Renew mode
Resource abundance constraint type	Medium grade of vulnerability High vulnerability of economic and ecological systems Water resources development and water pollution	Water pollution	Water Environment treatment	√ Node protection √ Sewage treatment	Oriented mode
Economic and natural environment coupling impact type	High grade of vulnerability High vulnerability of social and ecological systems Dilemma of industrial choice	Industrial types undertaken	Industrial renovation	√ Industrial upgrading √ Industrial chain extension	Cascaded mode
Natural environment and public services coupling impact type	High grade of vulnerability High vulnerability of social and economic system Public services extension	Public services integration	Infrastructure government	√ Convenient services √ Industrial and city emergent	Equivalent mode
Public services and resource abundance coupling impact type	High grade of vulnerability Medium vulnerability of all subsystems Public space accessibility and connectivity	Space fragmentation	Ecological remediation	√ Hydrophilic green bank √ Water-green blend	Dredging mode
Economic-natural environment and public services multiple impact type	High-low grade of vulnerability High social and ecological systems Vacant and wasteful resources	Resources use efficiency	Reduction government	√ Increase & decrease contact √ Intensive use	Displacement mode
Economic-natural environment and resource abundance multiple impact type	High-low grade of vulnerability High-low economic system Industrial structure rigid	Space quality	Environmental Improvement	√ Outskirt planning √ Ecotourism	Outskirt mode
Integrated impact type	Low grade of vulnerability Low vulnerability of all subsystems Coordinated development	Resources overall planning	Integrated territory consolidation	√ Urban and rural city emergent √ Integration	Aggregative model

ernance of the grass-roots organization and the extinction of rural culture in the suburban village. 'Subject raise and rural order reconstruction' have become the focus of the region to reduce the vulnerability of social subsystems. Specifically, in order to improve the village governance system and reshape the social comprehensive renovation mode of the rural village appearance, it should embed the new rural development subject under the strengthening of the superior economic location.

(2) Natural environment constraint type. The regions of this type were mainly distributed on the west side of Dianshan Lake, which were affected by the water source protection plan of Shanghai City so it became an important crop planting area, and the agricultural output value was high. Under the dual restrictions of pursuing crop yield to increase farmers' income and low intensity agricultural development to prevent water pollution, the region was faced with the problems of agricultural environmental pollution caused by the increase of agricultural production capacity and the systematic vulnerability of cultivated land abandoned due to inefficient utilization of agricultural land. Development concepts of 'Cultivated land protection, capacity upgrading and leisure industry exploited' were the focus of reducing economic subsystem vulnerability. Specifically, it should pay attention to the ecological environment and integrate the farmland forest network and the natural texture of the river and lake water system under the premise of respecting nature.

(3) Public services constraint type. The regions of this type were concentrated in the middle parts adjacent to the center of Shanghai City and Qingpu District. In the process of land requisition and removal brought by rapid economic development, the development mode of government leading and multi-subject participation caused the differences of interest of the multiple subjects. In the process of the multi-agent game, the regional differences of government power, market power and social power imbalances and social public service coverage were formed. Along with these processes, the region had created serious issues regarding equity and efficiency in public services. 'Multi-subject coordination and step-by-step promotion' was the focus of reducing the vulnerability of the social subsystems. The regional renewal model with material space and social space as the object was the focus of future development. Specifically, by means of the transformation and quality improvement of public service facilities, the gradual and hierarchical social space menu control method was adopted to make rational use of social public space and improve the quality of the living environment and regional quality.

(4) Resource abundance constraint type. The regions of this type were mainly concentrated in the central, northern and southern parts of the Industrial Park and Agricultural Industrial Zone of Liantang in Qingpu District which had 579 criss-crossed rivers in the region. The quantity of industrial water demand and the regulation of water environmental quality had become important factors of vulnerability. 'Node protection and sewage treatment' had become an important way to reduce the vulnerability of ecosystems in the region; specifically, by means of planning the ecological nodes of the water network to regulate the water environment of the industrial park, strengthening the ecological function of the water corridor, and meeting the overall improvement of the service efficiency of the water ecosystem. The waterfront green belt width and vegetation coverage were increased to improve the water resource self-purification capacity. These steps should create multi-level water plant communities to isolate non-point source pollution for agricultural industrial areas. At the same time, the farmland landscape ecological clear ditch and the surrounding farmland drainage direction were added to avoid the contamination by farmland pollutants of the water environment.

(5) Economic and natural environment coupling impact type. The regions of this type were mainly concentrated in the northeast and southeast, distributed in Baihe and Liantang. Under the superior geographical conditions and economic location, these regions had the dilemma choice problems of industrial choice and industrial positioning. The soil parent material types in the southeast region are tidal reflux sedimentary parent material and lake sedimentary parent material. The high content of organic matter and the perfect irrigation and drainage facilities had become the dominant areas for the development of the agricultural industry. The northeastern region was close to the center of Shanghai and Kunshan Economic Development Zone, and it became an important area for industry development. 'Industrial upgrading and industrial chain extension' had become the focus of reducing vulnerability.

(6) Natural environment and public services coupling impact type. The regions of this type were mainly distributed within the service radius of about 25 km from the center of Qingpu District, and the internal infrastructure of the region was complete and the river resources were abundant. However, in response to the planning of 'one city, two wings and ecological livability' in Qingpu District, the region intended to separate the industrial development function from the residential function in order to alleviate the pressures of population and industrial agglomeration on the district center, as well as to achieve the 'one hour' economic service radius to develop high-quality residential industry and supporting infrastructure. However, under the influence of rigid index requirements and financial factors, only the related supporting facilities were rigidly arranged, ignoring the convenience of public services and the deep integration of urban facilities, resulting in the repeated construction of infrastructure. The above causes led to the development of confusion in these regions. Specifically, it should coordinate

the development of urban and rural industries under the concept of urban-rural equivalence, realize urban-rural interaction and orderly population agglomeration; promote the construction of regional science, education, culture and health with the goal of urban-rural equivalence of service facilities; and promote the rural economy and agricultural industrialization and rural economy marketization with public services.

(7) Public services and resource abundance coupling impact type. The regions of this type were mainly concentrated in the northern parts of Xianghuaqiao, about 30–40 km from the center of Qingpu District. With the rapid development of the agricultural industry, high-precision electronics industry and pharmaceutical industry, this region had the following problems: The division of land ownership in urban and rural areas, the insufficient quality and quantity of public service facilities, the fragmentation of space and the low utilization rate of public services caused by the fear of open space on the waterfront, the contradiction between the construction of flood control facilities and the recreational demand of residents, and the connection between the layout of facilities and the shore, which had become the factors affecting the social-ecological system vulnerability. The idea of 'Hydrophilic green bank and water-green blend' became the focus of reducing vulnerability. Specifically, on the one hand, the water green environment of the waterfront space should be repaired to create a safe and pleasant green shoreline, with opening of the green breakpoint, parks, wetlands, squares and other ways to improve the environmental quality. On the other hand, it should rely on the hydrophilic green bank to develop leisure and multi-function agricultural industry parks to stimulate the economic vitality of the river network.

(8) Economic-natural environment and public services multiple impact type. The regions of this type were mainly distributed in the east of Xianghuaqiao and the west of Zhujiajiao, outside the centralized construction region. The movement of the agricultural population to the central construction area and the industrial park, has caused problems of low efficiency, idle resources and waste of rural collective construction land, scattered distribution of residential areas and a large land area occupied by township enterprises. The resource utilization modes of increasing construction and gathering potential had become the focus for reducing vulnerability. Specifically, by means of the policies of 'similar to the construction region' to guide the land replacement, it should merge disjointed residential areas and employ intensive and economical land use modes to stimulate the reduction and promotion of construction land outside the construction regions.

(9) Economic-natural environment and resource abundance multiple impact type. The regions of this type were mainly distributed at the junction of Dianshan Lake, Qingpu District center and Shanghai City center, with better industrial, ecological environment and resource allocation. Restricted by the traditional industrial development concept, the industrial development in this region was self-contained, and the industrial cohesion was low, forming the tourism industry and leisure agriculture of the ancient town near the Dianshan Lake area, the processing industry and service industry in the near district center and the equipment manufacturing industry in the near city center. The development modes of 'outskirt planning and ecotourism' had become the focus of integrating multi-industry development to reduce the economic vulnerability. Specifically, it should take ecotourism as the background, combine it with the characteristics of the oldest water township in Zhujiajiao and the green space system of 'ring, corridor, garden and forest', rationally plan the country units, carry out the overall relocation of pollution industry, and form ecological, landscape, industry and other multi-functional complex ecological network nodes.

(10) Integrated impact type. The regions of this type were mainly distributed in Xiayang and Zhujiajiao, and the overall social-ecological system vulnerability was low. The development modes of 'urban and rural city emergence and integration' had become the focus of integrating multi-industry development to reduce economic vulnerability. Specifically, it should realize urban-rural interaction and urban-rural interworking through spatial integration, break down dual forms of business through industrial integration, and realize the development of urban-rural integration through factor sharing and overall planning.

5 Conclusions and prospects

5.1 Conclusions

(1) Rural social-ecosystem vulnerability is a process in which rural social-ecosystems have experienced external pressures and environmental changes, resulting in different states and responses of the carriers. It conforms to the vulnerability efficiency research framework of pressure input-state and response output.

(2) The efficiency evaluation model of EW-DEA based on the intersection of entropy weights was more reliable and accurate for evaluating rural social-ecosystem vulnerability. It can distinguish the logical relationships between social-ecosystem vulnerability indicators and deal with the distortion of evaluation results caused by multiple index weight dependence. At the same time, the model can overcome the problem of vulnerability ranking caused by the intentional fragmentation of the correlation between evaluation units and the inability to distinguish the size of effective units caused by the extreme weight distribution of the CCR-DEA model. It can also overcome the problem that the evaluation results caused by the high correlation of the evaluation unit produced by the calculation of the optimal solution by the principle of 'keeping the higher value, reducing the lower value' in the ACE-DEA model.

(3) Geographical factors still had an important impact on

the spatial differentiation of social-ecosystem vulnerabilities in economically developed rural regions. But their influence presented a structural spatial difference. They had a greater impact on the more structurally rigid social subsystem based on the combination of long-term social humanities and production and life style. At the same time, the influence of geographical factors presented the characteristics of typological attribute substitution and level transformation. The economic geographical factors coupled with human response behaviors and spatial attributes had a greater impact on the vulnerability of rural social-ecological systems than natural geographical factors. The influences of natural geographical factors on the social-ecological systems were more internalized into the background environmental elements with recessive characteristics.

(4) The geographical factors had a high spatial overlap with the distribution of social-ecological system vulnerability in the economically developed rural regions, and the level and modes of influence showed that vulnerability abilities caused by a single factor had weakened, yet the vulnerability abilities caused by multiple factors were enhanced. On the one hand, the developed rural regions had become an open system deviating from the equilibrium state under the rapid economic advancement. The singular natural geographical factors had been internalized into the environmental background of social-ecosystem vulnerability, which leads to the dilution of the independence of vulnerability in the process of subsystem element flowing and system fusion, and the attachment and transformation of attributes had even occurred. On the other hand, with the continuous impacts of social transformation, economic change, industrial replacement, and self-interest of human behaviors on this deviant equilibrium system, the abilities of economic geographical factors and multi-factor coupling factors to form vulnerability were more obvious. The formation process of this compound vulnerability was as follows: relying on the diversity of economic industries to change the vulnerability of economic subsystems, relying on the urbanization of human customs to change the vulnerability of social subsystems, and relying on the diversity of human needs changes the vulnerability of ecological subsystems. At the same time, under the influence of the differences of regional natural geographical location and the imbalance of system structures, the regional patterns of regional social-ecosystem vulnerability differentiation had finally come into being.

5.2 Prospects

(1) The threshold of the vulnerability index and the perfection of the system are the core of the vulnerability assessment of the village social-ecosystem. According to the definition of vulnerability, the formation mechanism and the characteristics of the case area, the SEE-PSR vulnerability index system may need to be improved in the following aspects. Considering the difficulty of data acquisition and representation, there was less application of an index of management in the output index (such as management ability, policy transparency, etc.). However, those kinds of indexes may have certain influences on the comprehensive abilities caused by vulnerability. Because of the requirement of index expansion verification of the DEA model, many indexes which may have great influences on the research accuracy may be eliminated in the correlation analysis of the input and output indexes. In view of the three DEA evaluation models selected, the redundancy rate and adjustment rate of the production index were not considered, which may lead to the lack of index threshold research. The actual distance data (distance from township center, distance from center of Qingpu District, distance from center of Shanghai City) were used to characterize the economic geographical attributes. However, the actual distances might change with the improvement of transportation infrastructure and means of transportation. Similarly, the application of internet and big data greatly reduces the influence of distance differences, so the influence of the spatio-temporal distance interaction on vulnerability needs to be further studied. At the same time, under the influence of survey data quantity, this research extended the farmer scale data to the regional scale, which may have limitations in the cross-scale applicability, and needs a practical test.

(2) Integrated territory consolidation is an important approach for reducing the vulnerability of rural social-ecosystems. It is an important measure for improving the comprehensive coping abilities and reducing the regional vulnerability to study the choice of the geospatial modes based on the vulnerability of the rural society and ecosystem. Although it had been involved in this research, it is still necessary to strengthen the specific measures and regulation timing of land consolidation, reclamation, development, restoration, management and protection for different regions in future research, and finally promote the sustainable and overall development of man and nature by means of a comprehensive regulation plan for the full-array ecosystems in the future.

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乡村社会-生态系统脆弱性空间分异的地理影响及其生态修复模式—以上海市青浦区为例

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摘要：脆弱性研究是可持续发展科学的核心问题和研究热点。本文引入“投入-产出”效率理论，构建“社会-经济-生态—压力-状态-响应”的村域社会-生态系统脆弱性分析框架，以上海市青浦区为例，采用数据包络模型、空间自相关模型、多元 Logistic 回归模型、地理探测器和层次聚类模型分析该区 184 个行政村社会-生态系统脆弱性的空间差异及其地理影响机制。研究结果表明:（1）基于熵权集结交叉的“投入-产出”效率模型对村域社会-生态系统脆弱性评价结果更具可信度和精确性，2018 年行政村社会-生态系统脆弱性空间上呈现由东向西逐渐降低的变化趋势，其脆弱性均值为 0.583，社会子系统脆弱成为限制该区社会-生态系统脆弱性降低的重要原因。（2）距上海市中心距离、距淀山湖距离、距青浦区中心距离和水域面积成为影响该区社会-生态系统脆弱性的 4 种主导地理因素，其地理影响力呈现系统结构空间差异和种类属性替代及程度转化。（3）依据地理因素影响力聚类分析将该区社会-生态系统脆弱性地理因素空间耦合模式分为 10 种，多地理因素耦合模式是主要决定类型，呈现中部多因素主导和两侧单因素主导并存的多元环状地域决定格局；且研究针对不同类型提出了 10 种修复区域社会-生态系统脆弱性的可行方式。该研究结果可为集“严格保护和大力发展”冲突区域的乡村空间重构、区域生态修复和可持续发展提供科学借鉴。

关键词：社会-生态系统；脆弱性评价；效率；地理因素；地理影响模式；生态修复；青浦区