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Ecological vulnerability assessment based on PSSR in Yellow River Delta

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ABSTRACT

Ecological vulnerability assessment of wetlands is a very important early-stage task for wetland protection, pollution treatment, ecological restoration and water resources utilization. On the basis of the study of vulnerability evolution mechanism of wetland ecosystem in the Yellow River Delta, this paper proposes a Pressure-Support-State-Response Model (PSSR) for ecosystem vulnerability assessment and employs a single-factor evaluation method. The proposed model is applied to assessing ecosystem vulnerability of wetland in Yellow River Delta (a case study of Dongying City). Research results show that: from 2005 to 2009, the ecosystem vulnerability of wetlands in Yellow River Delta was 0.62, and 0.68 from 2010 to 2014; the ecosystem vulnerability grade is moderately vulnerable during the two periods. Generally speaking, regional ecosystem vulnerability slightly decreases. More efforts should be made to protect and restore the ecosystem and prevent it from deterioration and wetlands degradation. This study may provide a theoretical support for wetland protection, management, exploitation and policy making in the Yellow River Delta.

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The *Convention on Wetlands of International Importance Especially as Waterfowl Habitat* signed in 1971 provides an internationally accepted definition of wetlands: “wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6 m” (Ding et al., 2007). The Yellow River Delta is located in north of Shandong province, the downstream of the Yellow River and south-west of Bohai Bay. It is a neoteric delta, which starts from Ninghai and ends at Taoer River at north-west, and Zimai Stream mouth at south-east. The Yellow River Delta also includes a recently-formed alluvial plain, with apex at Yuwa (Wang, 2005).

Wetlands in the Yellow River Delta are undergoing adverse influence by water and sand in the upstream of the Yellow River, regional climate change and human activities. As a result, wetlands have reduced in scale, lost biodiversity and reduced water storage capacity. As natural wetlands disappear, artificial ones are expanding, which reduces self-recoverability of the ecosystem and increases the vulnerability (Han, 2009). The uniqueness, representativeness and importance of wetlands in the Yellow River Delta arise the attention of the academic circle. This has become a key focus of researches on ecosystem (Carreno et al., 2008; Musacchio and Coulson, 2001.). Scripps Orbit and Permanent Array Center (SOPAC) is applied to constructing global ecosystem vulnerability index (Wang et al., 2009). In recent years, IPCC did a research on the consequence of rising sea level and climate change (IPCC, 2001). Elrich studied ecosystem vulnerability by human interference (Elrich and Elrich, 1991). These researches focus on ecological vulnerability assessment of one specific environment condition or a specific system.

China started the research on wetlands since the 1960s. Wang X. et al. employed remote sensing and GIS technology to measure wetlands in the Yellow River Delta and revealed the influence of human activities on wetland degradation (Wang et al., 1996; Wang and Li, 1997; Cui et al., 2005; Huang et al., 2003; Lei et al., 2013). Xu X. et al. provided grading assessment on the possibility of risks concerning wetlands in the delta and pointed out an index and formula to measure ecological loss and assess ecological risks, which was conductive to the comprehensive assessment of ecological risks of wetlands in the Yellow River Delta (Xu et al., 2001; Lu et al., 2001; Sun, 2001; Wang et al., 2008). Dai X. et al. used traditional AHP to assess the quality of wetland ecosystem in the Yellow River Delta (Dai et al., 2007; Ou et al., 2013). Ecological vulnerability assessment is a main focus of ecosystem vulnerability. At the present, many assessment methods are available, including

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Fuzzy Evaluation Method, Artificial Neural Network Method, Principal Component Analysis Method and Comprehensive Evaluation Method. These methods have both advantages and disadvantages. For example, Fuzzy Evaluation Method stresses much on extreme value, which results in a loss of data. The accuracy of Artificial Neural Network Method is not high enough and it requires a large amount of original data to support the evaluation result. The comprehensive evaluation function is unclear when the principal component load has both plus sign and minus sign. Therefore, based on "pressure-support-state-response" assessment model, this thesis uses single-factor evaluation method to assess the ecosystem vulnerability of the Yellow River Delta, hoping to reflect the dynamic change of ecosystem vulnerability in a simple and direct way.

1. Research method

1.1. Assessment system

The Pressure-State-Response Model (PSR) was first put forward by Canadian statisticians Rapport and Friend in 1979. Later in 1980s and 1990s, OECD (Organization for Economic Co-operation and Development) and UNEP (United Nations Environment Programme) co-developed a framework for studying environment problems and interactive relation between the environment and human beings. In this framework, human obtains energies that are necessary for their survival from the Nature and discharges waste to the environment, thus changing the environment quality and the storage of natural resources. Environment also poses an influence on social-economic activities and requires society to change correspondingly. The focus of the model was the function and the structure of the wetland ecosystem. In this model, a wetland vulnerability evaluation index system is established, concerning resources, environment, ecology, society and economy. Such index system has a solid and scientific support, and is applicable and widely accepted. However, the indexes may be overlapping. The cause-and-effect of pressure and state cannot be simplified. And it is more proper to be applied to large-scale research, rather than detailed evaluation.

Consequently, when selecting indexes, this thesis takes into consideration the capacity of the wetland ecosystem of accepting overload human activities and proposes a "Pressure-support-state-response" (PSSR) model based on PSR model. It analyzes the quality of the wetland ecosystem, the influence of human activities on wetland, the support of wetland under pressure and the changes of the state of wetland. According to the model, the human society should response to wetland changes and we have the obligation to prevent wetlands from degradation. Thus, the construction of ecological vulnerability assessment indexes of wetland in the Yellow River Delta should coordinate social, economic, ecological and comprehensive factors. Based on the "pressure-support-state-response" model and according to real situation in the research area, this thesis adopts weighed sum method to calculate weight of indexes and weigh indexes according to expert experience method. At the same time, reliability, completeness, dynamism and operability are considered in index selection. Pressure indexes include human activity index and land resource index. Support index is primary productivity index. State indexes are wetland ecological state index and resource state index. Response indexes contain social-economic variation index and resource-environment variation index. The evaluation index system for wetland ecosystem vulnerability in the Yellow River Delta is shown in Table 1 and Fig. 1.

1.2. Assessment method

Ecological vulnerability assessment is a key concern of the study of ecosystem vulnerability. At the present, common assessment methods are Fuzzy Evaluation Method, Artificial Neural Network Method, Principal Component Analysis Method and Comprehensive Evaluation Method. These methods have both advantages and disadvantages. For example, Fuzzy Evaluation Method emphasizes much on extreme value. As a result, a large amount of data is missing. Artificial Neural Network Method is not high in accuracy and thus a large amount of original data is needed to support the evaluation result. Each method has its own limitations and poor in revealing the mechanism. Therefore, this thesis proposes a "pressure-support-state-response" (PSSR) model and takes into account the fact that evaluation indexes cannot reflect the quality of the ecosystem in a linear way (Holling, 1973). To address it, this thesis draws merit from the widely applied logistic growth parabola to evaluate single index.

$$P = \frac{1}{1 \pm e^{(a-bR)}} \tag{1}$$

Table 1
The evaluation index system for wetland ecosystem vulnerability.

target	criterion	evaluation index	calculation of index
Pressure (0.3)	land pressure (0.5)	land reclamation rate	agricultural land area divided by the total area of the study area
	human pressure (0.5)	the density of population 0.5	the total area of population divided by the study area
		human disturbance index 0.5	the total area of construction and agricultural land artificial wetland divided by the study area
support (0.2)	primary productivity	normalized difference vegetation index (NDVI) 0.5	(TM4-TM3)/(TM4+TM3)
		afforestation area percentage 0.5	the total area of afforestation divided by the study area
state (0.4)	organization (0.4)	Shannon's diversity index (SHDI) 0.5	the total for the product of the proportion of landscape accounted and its logarithmic $SHDI = \sum_{i=1}^{m}(P_i \ln P_i)$
		Shannon's evenness index (SHEI) 0.5	SHDI divided by logarithmic number of landscape types $SHEI = \frac{\sum_{i=1}^{m}(P_i \ln P_i)}{\ln m}$
	service (0.3)	ecological water percentage 0.5	ecological water use of area divided by the total water use
		pollution load 0.5	waste water containing ammonia nitrogen by per milliliter
	elastic (0.3)	elastic degree of wetland evaluation	the total for the product of the proportion of landscape types accounted and its flexibility $ECO_{res} = \sum_{i=1}^{m}(P_i \times B_i)$
Response (0.1)	resource-environment variation	the wetland area of change 0.5	nature wetland and artificial wetland
	social-economic variation	gross domestic product 0.5	the total output divided by total population

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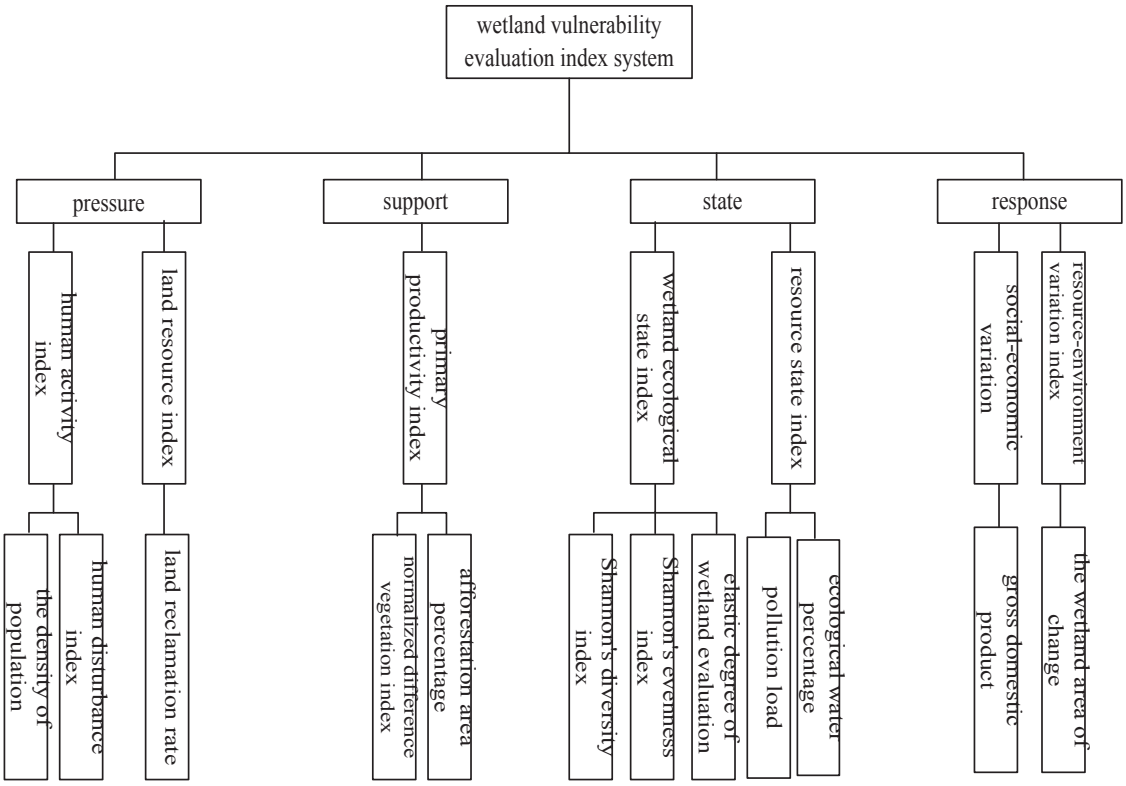


Fig. 1. Wetland vulnerability evaluation index system.

where, P is the ecosystem vulnerability value of each index (dimensionless value);

R is the measured value of each index (%);
a, b are constants, when $R = 0.01$, $P \approx 0.001$; when $R = 0.99$, $P \approx 0.999$, a and b are 4.595 and 9.19 respectively.

If the evaluation index is of growth type, in other word, if the index value is in direct proportion to the grade of quality evaluation of the ecosystem, Eq. (2) is applied to this case.

$$P = \frac{1}{1 - e^{(4.595 - 9.19R)}} \tag{2}$$

In contrary, if the index value is in inverse proportion to the grade of quality evaluation of the ecosystem, Eq. (3) is applied to this case.

$$P = \frac{1}{1 + e^{(4.595 - 9.19R)}} \tag{3}$$

P embodies the relationship between a single factor and the ecosystem vulnerability. For a single factor, the bigger P is, in other word, the larger the index value is, and the more vulnerable the ecosystem will be.

R is the change of rate of a single index in a given time. When R is above 0, the evaluation index presents a positive growth. Otherwise, it presents a negative growth.

1.3. Evaluation criteria

Given influential factors of ecosystem vulnerability, driven mechanism of ecosystem vulnerability and ecological conditions are distinct in different regions, it is hard to consider all influential factors when assessing ecosystem vulnerability of a specific region. Because of so, there is yet a unified standard or mode for ecosystem vulnerability assessment. Wetlands in the Yellow River Delta have a unique ecosystem. Influential factors and driven mechanism are complicated and uncertain. According to real situation and previous researches (Jiang, 2005; Wu, 2009), the grading standard is ranked from the highest to the lowest score to reflect wetland ecosystem vulnerability in the Yellow River Delta, as shown in Table 2.

1.4. Weight calculation

Weight calculation has been studied by foreign scholars for a long time. Common methods include Fuzzy Classification Method, Analytic Hierarchy Process, Stepwise Regression Method, Grey Correlation Method and Principal Component Analysis Method, to name just a few. In this thesis, expert experience method is introduced to allocate weight to indexes. To be reliable, complete, dynamic and operable, weight calculation is shown in Table 1.

2. Ecological vulnerability assessment of wetlands in the Yellow River delta

2.1. Data acquisition and analysis

Dongying City is located at north of Shandong province (36°55′-38°10′N, 118°07′-119°10′E), and is a key city in the Yellow River Delta, with Bohai Sea at its the east, Beijing-Tianjin-Tangshan Economic Zone at its north, Shandong Peninsula Economic Zone at its south, and many inland cities to the west. It also faces Japan and Korea across the sea. More importantly, it is a key joint of the Circum-Bohai Sea Economic Zone, a crucial part of Shandong peninsula urban agglomeration, the bridge connecting Central

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Table 2
Wetland ecological environment vulnerability classification.

Comprehensive evaluation	Class	EVI	Wetland ecological features
potential vulnerability	Class one	0 −0.2	Wetland landscape is good. Structure is complete. Dynamic is normal. Restore ability is very strong.
Micro vulnerability	Class two	0.2 −0.4	Wetland landscape is better.Structure is relatively complete. Dynamic is relatively normal. Restore ability is relatively strong.
Mild vulnerability	Class three	0.4 −0.6	Wetland landscape is change to some extent. Structure is complete. Vitality is deteriorative. Function level has certain degradation. Capacity for recovery is diminished.
moderate vulnerability	Class four	0.6 −0.8	Wetland landscape is received considerable damage. Structure is crushing and vitality is poor. Function level have serious degradation.Partial function is loss. Rapid response to outside interference.
Severe vulnerability	Class five	0.8 −1.0	Wetland landscape is completely destroyed, Structure is crushing and dynamic is worse. Most of the wetland function is loss. Quickly response to external interference.

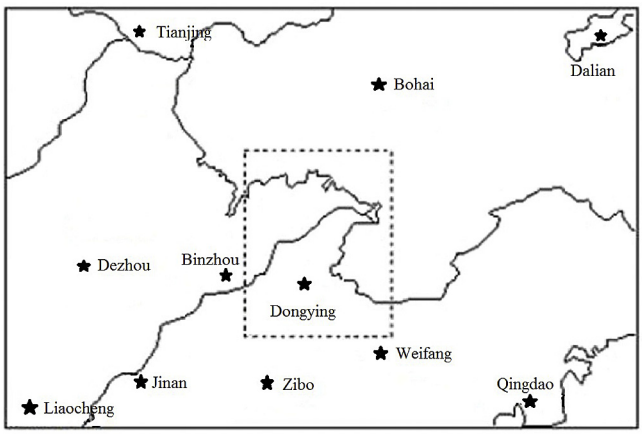


Fig. 2. The location of the research area.

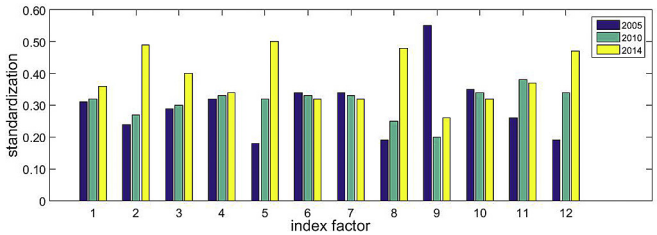


Fig. 3. Variation of indexes after standardization.

China Economic Zone and Northeast Economic Zone and a hub for Beijing-Tianjin-Tangshan Economic Zone and Jiaodong Peninsula Economic Zone. The location of the research area is shown in Fig. 2.

Data in this thesis is sourced from *Statistical Yearbook of Shandong Province*. Relevant information is interpreted by remote sensing data. Indexes of ecosystem vulnerability in the research area are shown in Table 3. Variation of indexes after standardization is shown in Fig. 3.

2.2. Assessment results

Pressure, support, state, and response of wetlands ecosystem are weighted and added up to obtain a comprehensive ecological vulnerability index of wetland in the Yellow River Delta. As a result, the ecosystem vulnerability of wetlands in the Yellow River Delta can be analyzed in a quantified way. Evaluation results are shown in Table 4 and Table 5.

3. Discussion and analysis

This thesis does a quantitative analysis of ecosystem vulnerability of wetlands in the Yellow River Delta. After normalization, vegetation index, landscape diversity index, evenness index, average degree of wetlands elasticity and variation of the scale of wetland all are negative values. It implies that these indexes grow adversely. In other word, they are decreasing or have decreased. Indexes that go against the ecosystem quality are positive values, suggesting that human activities are damaging the quality of the wetland ecosystem. Results show that from 2005 to 2010, the comprehensive evaluation index of ecosystem vulnerability is 0.62, while that from 2010 to 2014 is 0.68. The ecosystem vulnerability grade is moderately vulnerable (0.6–0.8). It implies that the wetland ecosystem is damaged and the quality is on the decrease. The system structure is unstable with poor vitality. The ecological function is degraded. Some functions are even lost. The system has a quick response to external interference.

Two points can be seen from Tables 1 and 2, one is normalized difference vegetation index, afforestation area percentage and

Table 3
Indexes of ecosystem vulnerability in the research area.

index factor	number	2005	2010	2014	2005–2010 R_1	2010–2014 R_2
land reclamation rate	1	0.4615	0.4741	0.5163	0.0125	0.0422
the density of population	2	2.257	2.5467	4.611	0.2897	0.8106
human disturbance index	3	0.5947	0.623	0.8186	0.0283	0.1957
normalized difference vegetation index (NDVI)	4	−4.6229	−4.819	−4.998	−0.1961	−0.179
afforestation area percentage	5	0.0037	0.0063	0.01	0.0027	0.0037
Shannon's diversity index (SHDI)	6	1.736	1.7001	1.6694	−0.0359	−0.031
Shannon's evenness index (SHEI)	7	0.724	0.709	0.6962	−0.015	−0.013
ecological water percentage	8	0.0198	0.0374	0.0509	0.0176	0.0136
pollution load	9	39.794	14.4897	18.7002	−0.6359	0.2906
elastic degree of wetland evaluation	10	0.5331	0.5174	0.4906	−0.0157	−0.027
the wetland area of change	11	333,427	487,110	456,770	0.4609	−0.0623
gross domestic product	12	64,907	116,800	157,486	0.7995	0.3483

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Table 4
Ecosystem vulnerability valuation results of the study area in 2005–2010.

index factor	the value of measure R_1	individual evaluation index P_i	weight W_i	comprehensive evaluation value
land reclamation rate	0.0125	0.0112	0.15	0.62
the density of population	0.2897	0.1264	0.075	
human disturbance index	0.0283	0.0129	0.075	
normalized difference vegetation index (NDVI)	−0.1961	0.9983	0.1	
afforestation area percentage	0.0027	0.9898	0.1	
Shannon's diversity index (SHDI)	−0.0359	0.9928	0.08	
Shannon's evenness index (SHEI)	−0.0150	0.9913	0.08	
ecological water percentage	0.0176	0.9883	0.06	
pollution load	−0.6359	0.0001	0.06	
elastic degree of wetland evaluation	−0.0157	0.9913	0.12	
the wetland area of change	0.4609	0.5888	0.05	
gross domestic product	0.7995	0.9400	0.05	

Table 5
Ecosystem vulnerability valuation results of the study area in 2010–2014.

index factor	Measuring valuation R_1	individual evaluation index P_i	weight W_i	comprehensive evaluation value
land reclamation rate	0.0422	0.0147	0.15	0.68
the density of population	0.8106	0.9456	0.075	
human disturbance index	0.1957	0.0575	0.075	
normalized difference vegetation index (NDVI)	−0.1790	0.9981	0.1	
afforestation area percentage	0.0037	0.9897	0.1	
Shannon's diversity index (SHDI)	−0.0310	0.9925	0.08	
Shannon's evenness index (SHEI)	−0.0130	0.9911	0.08	
ecological water percentage	0.0136	0.9887	0.06	
pollution load	0.2906	0.1274	0.06	
elastic degree of wetland evaluation	−0.0270	0.9922	0.12	
the wetland area of change	−0.0623	0.9943	0.05	
gross domestic product	0.3483	0.1988	0.05	

elastic degree of wetland evaluation are large and higher weights, the other is the rates of population density, human disturbance index and pollution load are large. From the analysis of these two points, normalized difference vegetation index, afforestation area percentage and elastic degree of wetland evaluation must be controlled for improve ecosystem vulnerability of wetlands in the Yellow River Delta, people need to have strong concern on reducing the growth rates of population density, human disturbance index and pollution load, especially the pollution load increased 1000 times in five years. People should survive and develop at the same time to rationally deal with garbage pollution.

4. Conclusions

(1) From 2005 to 2010, the comprehensive ecological vulnerability index of wetland in Yellow River Delta vulnerability was 0.62 and 0.68 from 2010 to 2014. The results show that wetland ecosystem in the Yellow River Delta is moderately vulnerable; and the vulnerability degree drops over the past 15 years.
(2) In index factors of ecosystem vulnerability of wetlands in the Yellow River Delta, the rates of population density, human disturbance index and pollution load are large, especially the pollution load increased 1000 times in five years. Ecosystem vulnerability of wetlands in the Yellow River Delta should be improved by common development of human and environment, rational planning and treatment of pollutant discharge
(3) The "pressure-support-state-response" model is a new try. Thus, there are weaknesses in this model. For example, the selection and grading standard are subjective to some extent and need further improvement.
(4) The single-factor assessment method is applied to conducting a quantitative assessment of wetland ecosystem vulnerability in the Yellow River Delta, in order to reflect ecosystem vulnerability evolution of the Yellow River Delta. It is objective and operable.

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References

Carreno, M.F., Esteve, M.A., Martinez, J., Palazón, J.A., Pardo, M.T., 2008. Habitat changes in coastal wetlands associated to hydro logical changes in the watershed. Estuar. Coast. Shelf Sci. 77, 475–483. http://dx.doi.org/10.1016/j.ecss.2007.10.026.
Cui, Baoshang, Li, Yinghua, Yang, Zhifeng, 2005. Management-oriented ecological water requirement for wetlands in the Yellow River Delta. J. Ecol. 25 (3), 606–613. http://dx.doi.org/10.3321/j.issn:1000-0933.2005.03.030.
Dai, Xin, Ding, Xilou, Chen, Yingjie, Wang, Guitian, Wang, Dongwei, 2007. The environmental quality appraisal of the wetland on the Yellow river delta by AHP method. Resour. Environ. Eng. 2007 (02), 135–139. http://dx.doi.org/10.3969/j.issn.1671-1211.2007.02.010.
Ding, Shengyan, Liang, Guofu, Yao, Xiaozong, Niu, Minggong, 2007. Study on the Landscape Pattern and Dynamics of Henan Yellow River Wetland [M]. Science Press. http://dx.doi.org/10.3321/j.issn:0375–5444.2004.05.002.
Elrich, P.R., Elrich, A.H., 1991. Healing the Planet [M]. Addison Wesley Publishing Company, New York.
Han, Mei, 2009. The Study of the Yellow River Delta Wetland Ecosystem [M]. Jinan: Shandong People's Publishing House, pp. 15–23.
Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 1973 (4), 12–23. http://dx.doi.org/10.1146/annurev.es.04.110173.000245.
Huang, Fang, Liu, Xiangnan, Zhang, Yangzhen, 2003. GIS-based eco-environmental

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vulnerability evaluation in West Jilin province. Geogr. Sci. 23 (1), 95–100. http://dx.doi.org/10.3969/j.issn.1000-0690.2003.01.017.
IPCC, 2001. Climate Change 2001: Impacts Adaptation and Vulnerability [R]. Cambridge University Press, London.
Jiang, Weiguo, 2005. Assessment of wetland ecosystem health in the Liaohe River Delta. J. Ecol. 25 (3), 155–200. http://dx.doi.org/10.3321/j.issn:1000-0933.2005.03.004.
Lei, Bo, Jiao, Feng, Wang, Zhijie, Liu, Yuanxin, Zhu, Letian, 2013. Eco-environment vulnerability evaluation and characteristics analysis in Yanhe river watershed. J. Northwest For. Univ. 2013 (03), 161–167. http://dx.doi.org/10.3969/j.issn.1001-7461.2013.03.31.
Lu, Xiaofeng, Wang, Tieliang, Sun, Yi, Zhang, Dan, Su, Fangli, Yuan, Xin, Zhang, Yulong, 2001. Ecological frangibility function evaluation of Shuangtai estuary wetland in Panjin. J. Green Sci. Technol. 2001 (04), 460–464. http://dx.doi.org/10.3969/j.issn.1000-1700.2011.04.014.
2010 Musacchio, L.R., Coulson, R.N., 2001. Landscape ecological planning process for wetland water fowl and farm land conservation. Landsc. Urban Plan. (56), 125–147. http://dx.doi.org/10.1016/S0169-2046(01)00175-X.
Ou, Chaorong, Sun, Songyu, Zhu, Qingke, Ye, Wen, 2013. Research progress of environment fragility in China. Anhui J. Anhui Agric. Sci. 2013 (08), 3619–3621. http://dx.doi.org/10.3969/j.issn.0517-6611.2013.08.117.
Sun, Yi, 2001. Ecological frangibility evaluation of Shuangtai estuary wetland in Panjin [D]. J. Green Sci. Technol. 2001.
Wang, Jieyong, 2005. The Environmental Vulnerability and its Land Use Effects in the Yellow River Delta [D]. Shandong Agricultural University, Jinan. http://dx.doi.org/10.7666/d.y729262.
Wang, Xianli, Li, Xiuzhen, 1997. Research progress of wetland at home and abroad. Chin. J. Ecol. 1997 (01) http://dx.doi.org/10.3969/j.issn.1009-2234.2012.05.023, 59–63+78.
Wang, Xianli, Bu, Rencang, Hu, Yuanman, Xiao, Duning, 1996. Analysis on landscape fragment of Liaohe delta wetlands. Chin. J. Appl. Ecol. 1996 (03), 299–304. http://dx.doi.org/10.13287/j.1001-9332.1996.0060.
Wang, Riyan, Zhao, Gengxing, Jiang, Shuqian, Wang, Ailing, Wang, Jing, 2008. Spatio-temporal variation of Eco-environment frangibility based on remote sensing and catastrophe theory: a case study of Kenli County in the Yellow River Delta. Chin. J. Appl. Ecol. 2008 (08), 1782–1788.
Wang, Ruiyan, Zhao, Gengxing, Zhou, Wei, Jiang, Shuqian, yuanwei, Qin, 2009. Assessment and dynamic changes of environmental vulnerability at county level a case study in Kenli County of the Yellow River Delta. J. Ecol. 2009 (07), 3790–3799. http://dx.doi.org/10.3321/j.issn:1000-0933.2009.07.041.
Wu, Shanshan, 2009. Analysis on Landscape Pattern Change and Ecological Environmental Vulnerability Assessment of the Southern Coastal Wetland of Laizhou Bay [D]. Shandong Normal University, Jinan.
Xu, Xuegong, Lin, Huiping, Fu, Zaiyi, 2001. Regional ecological risk assessment of wetland in the Yellow River Delta. Beijing J. Peking Univ. 37 (1), 111–118. http://dx.doi.org/10.3321/j.issn:0479-8023.2001.01.017.

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