Spatiotemporal Characteristics and Evolution Analysis of the Human-Sea Relationship Territorial System in the Bohai Rim Region from a Vulnerability Perspective (Postprint)

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Date: 2018-03-08T00:00:00+00:00

Abstract

Vulnerability has emerged as a frontier domain in global environmental change and sustainability science research. The human-sea regional system, as a crucial component of marine geography research, investigates the structural characteristics and evolutionary patterns of human-sea geographic spaces within specific geographical extents. Taking the Bohai Rim region as a case study, this paper first provides an overview of marine resources, marine scientific and technological capacity, human resources, and marine infrastructure, and analyzes the development trajectory of the marine economy; second, employing vulnerability as the analytical entry point, it utilizes the Set Pair Analysis method to examine the evolution of vulnerability and its influencing factors in the human-sea regional system of the Bohai Rim region; finally, it applies the triangular diagram method to conduct typological differentiation of the vulnerability of the human-sea regional system in the Bohai Rim region from 1996 to 2012, thereby proposing targeted strategies for vulnerability reduction. The results indicate that: (1) although the vulnerability indices of the human-sea regional system in the Bohai Rim region exhibited varied developmental changes, they all demonstrated a declining trend, with significantly enhanced stability; (2) the vulnerability of the human-sea regional system in the Bohai Rim region rarely fell into the single-subsystem vulnerability type; instead, the composite-subsystem vulnerability type and balanced vulnerability type were the predominant categories with higher frequencies of occurrence; (3) vulnerability reduction in the human-sea regional system can be achieved through measures including strengthening integrated land-sea coordination, optimizing the marine industrial structure, enhancing marine pollution control, advancing marine science and technology innovation, accelerating talent cultivation, and reinforcing infrastructure development.

Full Text

Vulnerability-Based Analysis of the Spatial-Temporal Dynamic Patterns of the Human-Sea Territorial System in the Bohai-Rim Region, China

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Abstract

Vulnerability in human-sea territorial systems represents a research frontier in regional sustainable development. Studies on human-sea systems are significant for both enriching theories of human-land territorial systems and promoting marine sustainable development. This paper first analyzes marine resources, marine science and technology capabilities, marine infrastructure, and marine economic development processes in China' s Bohai-rim region. Human-sea territorial systems comprise three subsystems: the human-sea resources and environment subsystem, the human-sea economic subsystem, and the human-sea society subsystem. Subsequently, combining set pair analysis, vulnerability assessment, and combination weighting methods, we examine evolution trends and major factors influencing human-sea territorial system vulnerability in the Bohai-rim region from 1996 to 2012. Overall results show a declining vulnerability trend for the region' s human-sea territorial system over the past 17 years. Shandong' s vulnerability index is smaller than other provinces; Liaoning' s vulnerability index, belonging to the second tier, declines most significantly; Hebei and Tianjin belong to the third tier with relatively higher vulnerability indices but greater potential for decline. Finally, we classify vulnerability types from 1996 to 2012 using triangle methodology. Results indicate that single-subsystem vulnerability occurs less frequently than balanced and complex subsystem vulnerabilities. To reduce vulnerability in the Bohai-rim region, measures should include strengthening land-sea coordination, optimizing marine industrial structure, enhancing marine pollution control, advancing marine science and technology innovation, accelerating talent cultivation, and improving infrastructure development. This paper provides references for improving theoretical and methodological frameworks for coastal regional and human-sea territorial system vulnerability research across different regions.

Keywords: Human-sea territorial system; vulnerability; set pair analysis; triangle methodology; Bohai-rim region

Introduction

Vulnerability research originated from natural disaster studies [1]. As the field has expanded, it has evolved from focusing on vulnerability of natural environmental systems under global change to emphasizing integrated vulnerability of natural and human systems. It has become one of the frontier areas in global environmental change and sustainability science [2-3], demonstrating a trend of multidisciplinary integration. As fundamental analytical units for vulnerability research, coupled human-environment systems [5] and human-land systems [6-7] have become research hotspots. The human-sea territorial system represents an improvement upon the human-land territorial system [9-10] and has become an important research topic in marine geography [11].

Foreign literature on human-sea territorial system vulnerability is limited, with only scattered studies on marine-related aspects, such as Adrianto and Matsuda's [12] research on economic vulnerability of Japanese islands, and Guillamont [13] and Scott et al. [14] analyzing economic vulnerability of small island nations. Domestic research on coastal region vulnerability primarily focuses on impacts of natural disaster vulnerability on economies, such as Yang and Li [15] and Zhao et al. [16] examining marine disaster impacts on China's coastal economies, Li et al. [18] analyzing rough set theory and combination weighting methods for storm surge vulnerability assessment, and Yu et al. [19] conducting empirical analysis of marine economic system vulnerability in China' s coastal provinces and cities. Zhao et al. [20] studied socioeconomic system vulnerability in coastal zones using Hebei Province as a case study, while Hou et al. [17] analyzed tsunami vulnerability in Taizhou based on disaster risk assessment theory.

As labor, capital, and technology continuously accumulate in the Bohai-rim region, contradictions between population growth, coastal industrial development, and marine pollution have become increasingly prominent. Land-source pollutants have increased dramatically, traditional marine resources have been overexploited without effective alternatives, marine disasters occur frequently, and ecological damage such as shrinking coastal wetlands and marine protected areas has reduced the carrying capacity of nearshore resources and environments [22-23]. Industrial structures over-reliant on marine resources, immature new diversified economic structures, weak marine infrastructure support, and insufficient marine science and technology innovation [24] threaten the stability of the region' s human-sea territorial system. This paper examines the coupled human-sea resources-environment-society system from a vulnerability perspective, exploring development trends and influencing factors through multi-element, multi-flow, and multi-cycle characteristics, providing a new paradigm for human-sea territorial system research with important theoretical and practical significance.

A human-sea territorial system is a complex system formed by the interaction of human and marine elements in a specific region according to certain laws, possessing characteristics of territoriality and risk [25-26]. Synthesizing definitions of human-sea territorial systems and vulnerability, this paper defines the connotation of human-sea territorial system vulnerability: due to internal structural constraints and external pressures or disturbances, combined with insufficient response and recovery capacity, the system becomes damaged—a result of both internal and external factors. Vulnerability, as an essential attribute of human-sea territorial systems, changes dynamically with internal structure and external disturbance factors, representing a dynamic evolutionary process.

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1 Regional Overview

The Bohai-rim region refers to the economic zone comprising the maritime and terrestrial areas of Liaoning Province, Hebei Province, Tianjin Municipality, and Shandong Province surrounding the Bohai Sea [27], including parts of the Yellow Sea coastal areas.

1.1 Marine Resources The Bohai Sea is China' s largest inland sea, consisting of the Bohai Strait and central basin, with a sea area of approximately [Figure 1: see original paper]. It is rich in marine biological resources, mineral resources, and marine energy resources. In 2012, marine capture fishery and mariculture production . Proven oil reserves reached , accounting for 44.9% of the national total. Natural gas reserves were , with recoverable reserves . In 2012, crude oil and natural gas production accounted for 72.2% and 25.8% of national production, respectively.

The Bohai-rim coast primarily includes the Northeast Salt District, Changlu Salt District, and Shandong Salt District, accounting for of national production in 2012. The region' s marine energy resources are abundant, with a theoretical wave energy capacity of 2841.1 kW, developable tidal energy above 500 kW, and technically developable salinity gradient energy of kW. Wind power generation reached kWh in 2012. The region has 规模以上港口生产用码头泊位数 with throughput exceeding 72.5.9 million tons at large ports and .

Table 1 Marine resources of the Bohai-rim region in 2012

1.2 Marine Economy Leveraging abundant marine resources, well-established facilities, and strong scientific research capabilities, the marine economy has become the most promising and dynamic growth area in the Bohai-rim region. After the Tianjin Binhai New Area, Liaoning Coastal Economic Belt, and Shandong Peninsula Blue Economic Zone became national strategic plans, marine economy further drove regional rapid development. Table 2 shows that regional marine economic development is unbalanced, with significant disparities due to differences in resource-environment conditions and socio-historical development. The proportion of marine economic output value to national marine economic output varies across years. Marine economic development is a driving force for regional economic growth. From 1996-2012, the average annual growth rate of marine economic output value far exceeded regional GDP growth. Marine industry output value continuously increased, directly and indirectly contributing to regional GDP growth .

Table 2 Marine economic development in the Bohai-rim region

2 Methodology

2.1 Indicator System Construction Based on characteristics of human-sea territorial systems, we divide them into three subsystems: human-sea resources-environment, human-sea economy, and human-sea society. Drawing on relevant research [29-32] and following principles of scientific rigor, data availability, operability, and representativeness, we construct a vulnerability evaluation indicator system with 19 indicators. The system has three layers: the target layer (overall human-sea territorial system vulnerability), the criterion layer (economic subsystem E, resources-environment subsystem R, and social subsystem S), and the indicator layer. Indicators reflect both positive and negative impacts on system vulnerability—positive indicators show stronger vulnerability contribution when values are higher, while negative indicators show weaker contribution.

Data sources include China Marine Environmental Quality Reports, China Marine Statistical Yearbooks, China Marine Yearbooks, China Urban Statistical Yearbooks, and statistical yearbooks and bulletins of Bohai-rim provinces and cities for relevant years.

2.2 Weight Determination We use a combination weighting method integrating subjective weighting (Analytic Hierarchy Process, AHP) [33] and objective weighting (entropy method) [34] to determine indicator weights. Let w__p^i be subjective weights from AHP and w__p^j be objective weights from entropy method. According to the principle of minimum relative information entropy, the combined weight w__p is calculated to make subjective and objective weights as close as possible.

2.3 Evaluation Model and Steps Set Pair Analysis (SPA), proposed by scholar Zhao Keqin [35], is a quantitative analysis theory for multi-objective decision-making and multi-attribute evaluation. Human-sea territorial systems, influenced by numerous factors, exhibit typical uncertainty characteristics in vulnerability evolution. As vulnerability is an attribute of these complex systems, SPA is appropriate for this research.

The basic SPA concept involves analyzing the identity, difference, and opposition of two sets' characteristics under a specific problem context, establishing their certain and uncertain relationship. The connection degree expression is: = a + bi + cj, where a, b, c represent identity, difference, and opposition degrees respectively, with i [-1,1] and j = -1.

For vulnerability evaluation, let E be the human-sea territorial system vulnerability problem with m evaluation schemes H_k ($k = 1,2,\cdots,m$), each having n indicators I_p ($p = 1,2,\cdots,n$). The evaluation matrix D is formed with indicator weights $W = \{w_1, w_2, \cdots, w_n\}$. We determine optimal solution set $X = \{x_1, x_2, \cdots, x_n\}$ and worst solution set $Y = \{y_1, y_2, \cdots, y_n\}$. The connection degree u_k between scheme H_k and optimal set X is:

$$u_k = a_k + b_k i + c_k j$$

where a_k and c_k are identity and opposition degrees between indicator d_{kp} and sets X and Y. The closeness degree r_k of scheme H_k to the optimal solution is defined as:

$$r_k = a_k / (a_k + c_k)$$

The r_k index reflects the closeness between evaluated scheme H_k and optimal set X. A larger r_k indicates higher closeness. This paper uses r_k to reflect vulnerability intensity—when r_k is smaller, system vulnerability is lower [36-37].

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3 Evaluation Results

Based on SPA, we calculate vulnerability indices for the Bohai-rim region from 1996-2012 .

Table 4 Vulnerability evaluation results for human-sea territorial systems in the Bohai-rim region

Results clearly show temporal trends and regional differences. From 1996-2000, all regional vulnerability indices declined, with the largest drops in Liaoning, Tianjin, Shandong, and Hebei (0.48, 0.402, 0.319, and 0.264 respectively). During 2000-2004, Hebei and Tianjin’ s indices remained relatively stable while Liaoning and Shandong showed slight declines. From 2004-2005 and 2008-2009, indices briefly rebounded. During 2001-2004, 2005-2008, and 2009-2012, Tianjin’s index declined continuously, rebounded in 2005-2006, then remained stable. Liaoning and Shandong showed continuous decline during 2000-2005 and 2010-2011, with Liaoning’ s decline significantly greater than Shandong’ s.

Throughout the study period, Hebei’s vulnerability index was consistently high, showing substantial decline but still with considerable room for improvement compared to Shandong. Tianjin and Liaoning ranked second; after 2001-2012, Tianjin’ s index showed no significant change while remaining relatively high with improvement potential. Although Liaoning started with a high index, it showed the greatest decline. Shandong maintained relatively low vulnerability with limited room for further reduction.

3.1 Human-Sea Economic Subsystem Analysis The Bohai-rim region exhibits uneven marine industry development and unreasonable industrial structures. Hebei' s marine three-industry ratio was 0.2:66.7:33.1, with excessive secondary industry and insufficient tertiary industry. Tianjin' s ratio was 4.4:54:41.6, approaching the optimal structure but with small total output value, lagging behind nationally. Shandong' s ratio was 13.2:39.5:47.3, close to optimal but with primary industry exceeding national averages. Liaoning' s ratio was 7.2:48.6:44.2, approaching the optimal structure.

During the study period, the region' s marine secondary industry held clear advantages. Four traditional pillar industries—marine fisheries, marine oil and gas, marine transportation, and coastal tourism—accounted for 84.2% of added value in major marine industries, while emerging industries like marine medicine and marine power held small shares. Marine transportation and coastal tourism absolutely dominated the tertiary sector. In Liaoning, Dalian' s marine industry output exceeded half of the province's total marine economic output, while other coastal areas were significantly weaker. Marine science, technology, education, and management services grew rapidly, but the marine tertiary sector remained relatively weak.

3.2 Human-Sea Resources-Environment Subsystem Analysis Environmental pollution intensified and marine disasters became frequent in the Bohai-rim region. As a densely populated and industrialized area with a semi-enclosed topography, the region has poor water exchange capacity and fragile marine ecosystems. Continuous accelerated development, industrial pollution, and waste discharge from marine resource exploitation have severely polluted nearshore waters. In 2011, polluted sea area reached 10,300 km², accounting for 48.3% of the region' s waters, threatening marine life and continuously reducing suitable aquaculture areas while decreasing water transparency in tourist zones. Red tide pollution area expanded [38].

The region suffers from marine disasters like sea ice. In 2008, direct economic losses from sea ice disasters reached 6.318 billion yuan; in 2010, losses reached with mariculture damage area of and incalculable indirect losses [39].

3.3 Human-Sea Society Subsystem Analysis The Bohai-rim region possesses strong overall marine science and technology capabilities and human resources, but with significant regional differences. Shandong holds a dominant position, Tianjin and Liaoning are mid-to-upper level, while Hebei is weakest. Shandong and Liaoning' s scientific and talent resources concentrate in Qingdao and Dalian, with most personnel engaged in basic marine research and fewer applied interdisciplinary talents. Shandong' s scientific contribution rate leads significantly, with marine science and technology contributing to marine economy, far exceeding national averages [40]. Liaoning and Hebei show low transformation rates and slow industrialization progress.

4 Triangle Diagram Analysis

Using triangle methodology [41-42], we conduct time-series classification of human-sea territorial system vulnerability from 1996-2012 to intuitively identify evolution trends and propose sustainable development strategies. The total vulnerability index V_T comprises resources-environment subsystem vulnerability V_R, economic subsystem vulnerability V_E, and social subsystem vulnerability V_S: V_T = V_R + V_E + V_S.

We classify vulnerability into: single-subsystem vulnerability type (resources-environment R, economic E, or social S), composite-subsystem vulnerability type (RE, RS, or ES), and balanced vulnerability type (RES). Based on SPA, we calculate each subsystem' s vulnerability proportion. Single-subsystem vulnerability occurs when one subsystem' s vulnerability proportion exceeds 50% of V_T. Composite-subsystem vulnerability occurs when the sum of two subsystems' vulnerabilities exceeds 50%. Balanced vulnerability occurs when no single subsystem or two-subsystem combination exceeds 50% .

Table 5 Vulnerability types of human-sea territorial systems in the Bohai-rim region, 1996-2012

Results clearly show vulnerability types and evolution trends. During the study period, single-subsystem vulnerability occurred 6 times, composite-subsystem vulnerability 26 times, and balanced vulnerability 32 times—the most frequent type. This indicates that single subsystems rarely determined overall vulnerability, while composite and balanced types dominated.

Trend analysis shows Tianjin' s system evolved from balanced vulnerability to composite economic-resource-environment vulnerability, indicating gradually decreasing economic subsystem vulnerability. Hebei and Liaoning' s vulnerability primarily manifested as balanced vulnerability among resources-environment and social subsystems, with relatively few coordinated years among all three subsystems. Shandong showed the most complex type changes, with resources-environment subsystem vulnerability becoming increasingly prominent during type transitions.

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5 Countermeasures for Vulnerability Reduction

Based on vulnerability type classification, we identify key influencing factors and propose targeted measures:

(1) Single-subsystem vulnerability types: Focus on problems within that specific subsystem. For resources-environment vulnerability, control resource exploitation scale, strengthen renewable resource cultivation and non-renewable resource exploration, develop comprehensive resource utilization industries, strengthen land-based and marine pollution source monitoring, control land pollutant discharge into the sea, improve solid waste project management, enhance oil production and marine dumping project oversight, accelerate remediation of key polluted sea areas, and improve emergency response plans for oil and chemical spills.

(2) Composite-subsystem vulnerability types: For economic-social subsystem vulnerability, coastal regions should leverage their advantages to cultivate extended marine industry chains with relative advantages, strengthen land-sea industry coordination, and promote coordinated development. Under strengthened land-sea coordination, optimize resource allocation, coordinate marine three-industry proportions, and continuously advance marine industrial structure upgrading. Increase science, technology, and research investment, encourage enterprises and research institutions to focus on achievement transformation, and develop new marine industries through transformed achievements. Accelerate talent cultivation to establish a pool of professionals capable of breakthrough technologies and high-tech marine development. Strengthen port facilities and transportation construction, expand port economic hinterlands, and advance marine observation systems, marine data collection and sharing platforms, and new energy infrastructure.

(3) For composite-subsystem and balanced vulnerability types (RES): Control resource exploitation, improve resource utilization efficiency, strengthen environmental protection, enhance three-waste utilization, increase science and education investment, and strengthen infrastructure construction. Different provinces should focus on adjusting aspects with higher vulnerability according to their specific conditions.

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6 Conclusion and Discussion

Human-sea territorial systems constitute an important component of human-land relationship research. This paper employs set pair analysis and triangle methodology to study vulnerability development trends and types in the Bohai-rim region from 1996-2012. SPA results show overall declining vulnerability indices and significantly enhanced stability. Triangle methodology reveals that single-subsystem vulnerability occurred less frequently, while composite-subsystem and balanced vulnerability dominated. Vulnerability reduction can be achieved through strengthening land-sea coordination, optimizing marine industrial structure, enhancing marine pollution control, advancing marine science and technology innovation, accelerating talent cultivation, and improving infrastructure.

Vulnerability research represents a frontier topic in global environmental change and sustainability science. Human-sea territorial systems are complex coupled systems whose development is disturbed by internal factors, human activities, and external environments. This paper innovatively introduces vulnerability into Bohai-rim human-sea territorial system research, exploring regional spatial structure characteristics and evolution patterns through multi-element and multi-scale analysis, providing a new paradigm for such research. Given the system' s complexity, future research should focus on scientifically characterizing vulnerability mechanisms and driving forces under disturbance factors.

References

[1] Janssen M A, Schoon M L, Ke W M, Börner K. Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change. Global Environmental Change, 2006, 16(3): 240-252.

[2] Kates R W, Clark W C, Corell R, Hall M, Jaeger C C, Lowe I, McCarthy J J, Schellnhuber H J, Bolin B, Dickson N M, Faucheux S, Gallopin G C, Grübler A, Huntley B, Jäger J, Jodha N S, Kasperson R E, Mabogunje A, Matson P, Mooney H, Moore III B, O'Riordan T, Svedin U. Environment and development: sustainability science. Science, 2001, 292(5517): 641-642.

[3] Turner II B L, Kasperson R E, Matson P A, McCarthy J J, Corell R W, Christensen L, Eckley N, Kasperson J X, Luers A, Martello M L, Polsky C, Pulsipher A, Schiller A. A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences of the United States of America, 2003, 100(14): 8074-8079.

[4] Cutter S L, Boruff B J, Shirley W L. Social vulnerability to environmental hazards. Social Science Quarterly, 2003, 84(2): 242-261.

[5] 全球环境变化下人-环境耦合系统的脆弱性研究综述. 地理科学进展, 2010, 29(4): 454-462.

[6] 沿海城市人地关系地域系统脆弱性研究——以大连市为例. 地理科学, 2010, 30(10): 1722-1728.

[7] 区域人地耦合系统脆弱性及其评价指标体系. 地理科学进展, 2013, 32(1): 55-63.

[8] 社会生态系统及脆弱性驱动机制分析. 地理科学, 2014, 34(7): 1870-1879.

[9] 关于我国海洋经济地域系统时空特征研究. 地理科学进展, 2006, 25(5): 47-56.

[10] 从人地关系地域系统到人海关系地域系统：吴传均院士对中国海洋地理学的贡献. 地理科学, 2008, 28(1): 6-9.

[11] 环渤海地区人海资源环境系统脆弱性的时空分析. 地理科学, 2012, 34(11): 2214-2221.

[12] Adrianto L, Matsuda Y. Developing economic vulnerability indices of environmental disasters in small island regions. Environmental Impact Assessment Review, 2002, 22(4): 393-414.

[13] Guillaumont P. An economic vulnerability index: its design and use for international development policy. Oxford Development Studies, 2009, 37(3): 193-228.

[14] Scott D, Dawson J, Jones B. Climate change vulnerability of the US northeast winter recreation-tourism sector. Mitigation and Adaptation Strategies for Global Change, 2008, 13(5/6): 577-596.

[15] 海洋灾害脆弱性综合评价指标体系的设计. 海洋开发与管理, 2013, 32(3): 133-137.

[16] 沿海地区经济系统海洋灾害脆弱性评价研究——以山东省台风灾害为例. 中国海洋大学, 2014: 18-21.

[17] 基于遥感的台州市海啸脆弱性评估. 海洋通报, 2016, 6(2): 26-33.

[18] 我国沿海省市风暴潮灾害脆弱性组合评价研究. 海洋经济, 2013, 3(3): 21-25.

[19] 基于集对分析法的海洋经济系统脆弱性评价研究. 上海经济研究, 2016, 38(8): 12-23.

[20] 区域经济社会脆弱性研究——以河北省为例. 中国海洋大学, 2015: 37-38.

[21] 集约用海对海洋资源影响的评价方法. 生态学报, 2015, 35(16): 5458-5466.

[22] 基于能值分析的中国海洋生态经济可持续发展评价. 海洋开发与管理, 2013, 30(5): 51-54.

[23] 辽宁沿海地区人海经济系统脆弱性评价. 海洋经济, 2014, 4(1): 44-49.

[24] 环渤海地区海洋产业结构调整优化研究. 中国海洋大学, 2013: 37-38.

[25] 人海关系与人海关系地域系统理论研究. 辽宁师范大学, 2007: 24-29.

[26] 人海关系地域系统探讨. 地理科学进展, 2008, 27(4): 907-916.

[27] 环渤海地区海洋经济发展研究. 地理科学, 2007, 27(6): 761-767.

[28] 海洋经济脆弱性的研究综述. 大庆市城市脆弱性综合评价与动态演变研究, 2014, 34(5): 547-555.

[29] 论中国海洋经济的可持续发展. 海洋开发与管理, 2003, 25(4): 73-78.

[30] 海洋经济可持续发展能力评价及其在辽宁省的应用. 效率视角下的省域生态文明建设评价研究, 2009, 31(2): 288-294.

[31] 基于集对分析的方案评价决策矩阵与应用. 辽宁沿海地区人海经济系统脆弱性评价, 2014, 34(6): 711-716.

[32] 基于集对分析法 (SPA) 的中国旅游经济系统脆弱性测度研究. 系统工程理论与实践, 1996, 12(4): 67-72.

[33] 基于集对分析的鞍山市人地系统脆弱性评估. 地理科学进展, 2012, 31(3): 344-352.

[34] 环渤海区域近海污染特征分析及防治对策. 海洋开发与管理, 2012, 29(7): 71-75.

[35] 2010 年渤海海冰灾害特征分析. 自然灾害学报, 2011, 20(6): 87-93.

[36] 基于遥感与 GIS 的浙北近海海域生态系统健康评价. 生态学报, 2016, 36(24): 8183-8193.

[37] 景观多样性分析及其制图研究. 生态学报, 1995, 15(4): 345-350.

[38] 基于遥感与 GIS 的海口市景观格局动态演化. 地理科学, 2002, 22(7): 973-979.

[39] 中国煤矿城市经济系统脆弱性评价. 地理科学, 2016, 36(11): 3321-3328.

[40] 人海关系地域系统脆弱性研究. 地理科学, 2017, 37(8): 2563-2574.

[41] 三角图法在脆弱性评价中的应用. 地理科学进展, 2013, 32(1): 55-63.

[42] 基于三角图法的区域可持续发展评价. 地理科学, 2014, 34(7): 1870-1879.

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