Ocean and Coastal Management 167 (2019) 127–136

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Threshold of island anthropogenic disturbance based on ecological vulnerability Assessment——A case study of Zhujiajian Island

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ARTICLE INFO

Keywords:
Island ecological vulnerability
Anthropogenic disturbance
Threshold
Ecosystem management
Zhujiajian island

ABSTRACT

The accessibility of islands can be largely improved with fixed link to the mainland by the construction of sea-cross bridges and tunnels, which results in a rapid increase of tourists and economic income. Meanwhile the accelerated increase of built-up land will change the island land use deeply. As the main anthropogenic disturbance, the rapid change of land use and increase of tourists will set further pressure on the ecological vulnerability of islands. It is urgent to derive the threshold of anthropogenic influence on the island with fixed link to the mainland. Island Ecological Vulnerability Index (*IEVI*) is used to evaluate the ecological vulnerability of Zhujiajian Island. Land use and tourists change in the next 20 years is simulated to estimate the change of island ecological vulnerability. The main results are: 1) The ecosystem of Zhujiajian Island is in good condition now, with limited area at moderate and severe vulnerable status; 2) With the rapid increase of anthropogenic disturbance, the ecological vulnerability of the island tends to increase. During the research period 2015–2035 the area of severe vulnerability increases by 78%, and the area of mild vulnerability increases by 201 ha (33%). One third of the non-vulnerable area becomes vulnerable; 3) Based on the prediction of ecological vulnerability, the threshold of tourists in Zhujiajian Island is about 16 million per year. The upper limit of built up area is 2500 ha, which means 90% is already used. With the improvement of management effectiveness and waste treatment capacity, the island's anthropogenic disturbance threshold can be raised. The vulnerability based anthropogenic disturbance threshold analysis can provide a basis for viable island ecosystem management strategies.

1. Introduction

As an important component of the coastal zone, island is a carrier of many ecological functions and a key part of the marine protection (Chi et al., 2017). Island also has charming scenery that people are willing to come. But the traffic conditions have limited the development of the island tourism (Tzanopoulos and Vogiatzakis, 2011; Pan et al., 2016), and restricted the development of island economy. Therefore, many islands improved the traffic conditions through construction of sea-cross bridges and accelerated economic development (Madany et al., 1990; McElroy, 2007). The rapid development of economy is accompanied by the explosive growth of tourists and dramatic changes in island land use (Xie et al., 2018). Due to the limited area and resources of the islands and the relatively short operating time after the completion of many sea-cross bridges, the impact of the construction of sea-cross bridges on island ecosystems remains unclear (Tzanopoulos and Vogiatzakis, 2011; Cao et al., 2017). There are also cases of postpones of sea-cross bridge construction due to lack of knowledge about the impact on the island ecosystem, such as the Munnar Strait Bridge (Porta and Piazza, 2007).

With the construction of island-to-mainland projects, especially the "time-space compression" effect brought by sea-crossing bridges, the flow of materials, people, information, and services between islands and mainland will be strengthened (Patarasuk and Binford, 2012; Xie et al., 2018). Islands are lack of hinterland area, which is an important component of ecosystem resilience to the anthropogenic disturbance (Pan and Liu, 2014). In the case of Zhujiajian Island, the main anthropogenic disturbance is the rapid growth of tourists and extensive changes in the island land use (Xie et al., 2018). For the island that have fixed link to mainland by bridges, most of the research focused on the safety of the design of the sea-cross bridge, the performance of the material, the operational monitoring and the prediction of traffic flow, and result in the change of vegetation and environment quality (Aljarad and Black, 1995; Li et al., 2004; Gazder and Hussain, 2013; Jassim and Coskuner, 2017). With the development of remote sensing technology, it has become an effective method to quantify island land cover changes

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https://doi.org/10.1016/j.ocecoaman.2018.10.014
Received 20 June 2018; Received in revised form 15 October 2018; Accepted 15 October 2018

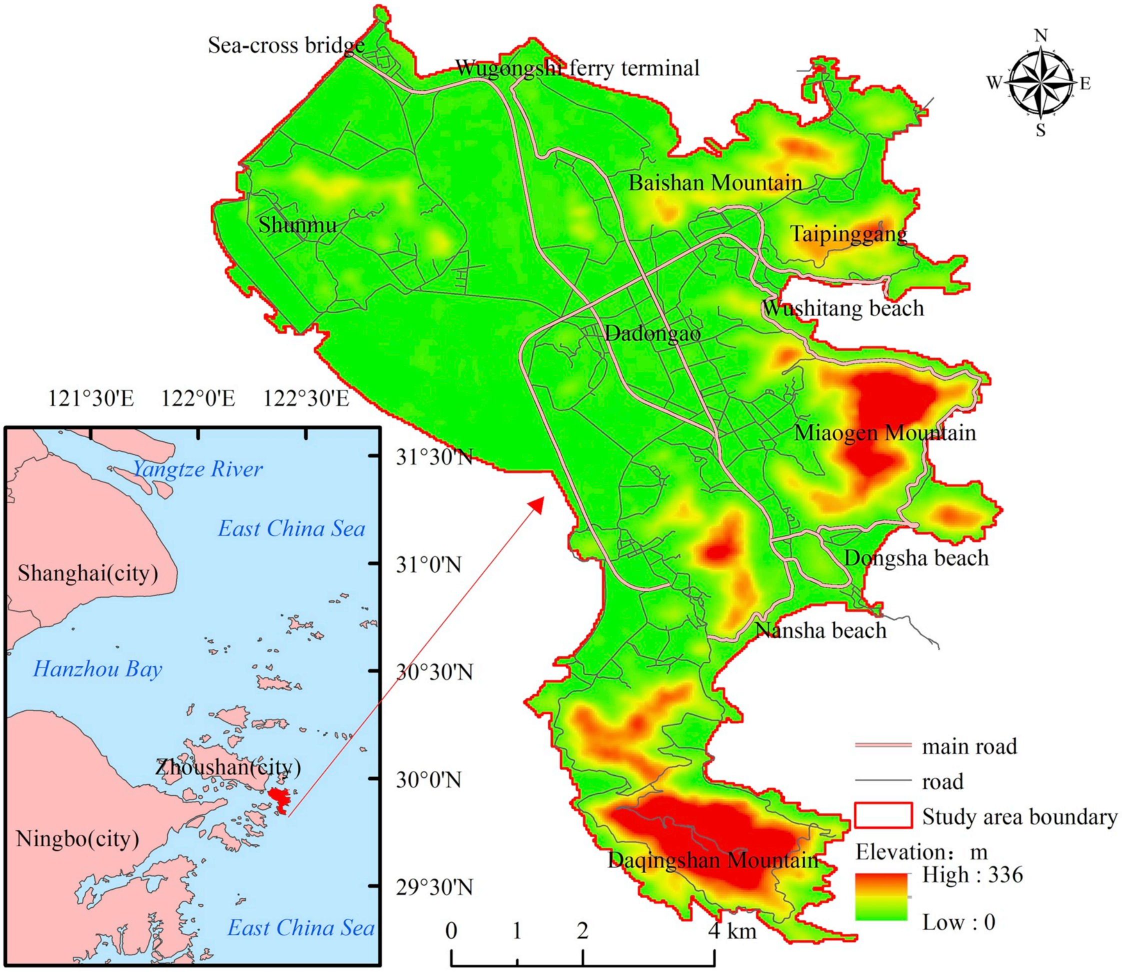

Fig. 1. Geographic location of the Zhujiajian Island.

(Li et al., 2011; Racault et al., 2014; Pan et al., 2016; Cao et al., 2017).

Some of the research analyzed the vulnerability of islands to specific hazards in the context of sea level rise and climate change (Pelling and Uitto, 2001; Morgan and Werner, 2014; Taramelli et al., 2015). Due to special characteristic of island ecosystems and the limitations of various data acquisition, the ecological vulnerability analysis of islands is rather limited (Tessler et al., 2015). Existing research about islands ecological vulnerability were focused on the vulnerability under global change, especially sea level rise (Mandal et al., 2017). At the same time, the ecological vulnerability was considered as an inherit characteristic of island, taking anthropogenic disturbance as regulatory factors (Kurniawan et al., 2016). Meanwhile, current research on the ecological vulnerability of islands was mainly focused on the ecological vulnerability assessment and the historical changes of island ecological vulnerability (Penghua et al., 2007; Fazey et al., 2010; Farhan and Lim, 2012), or the spatial heterogeneity of island ecological vulnerability (Chi et al., 2017). Therefore, the ecological vulnerability prediction and anthropogenic disturbance threshold analysis still need further investigation.

Along the coast of China, many islands have unique natural landscapes and marine cultures, which attract large number of tourists each year. After being connected with mainland, the island is often faced with serious anthropogenic disturbance, such as rapid land use change, and explosive growth of tourists (Cao et al., 2017; Xie et al., 2018).

It is urgent to estimate the threshold of anthropogenic activity in the island after being connected with mainland. The objective of this study is to identify the threshold of anthropogenic disturbance in Zhujiajian Island. To exempt the influence from the bridges between islands, we chose Zhujiajian Island at the end side of Zhoushan Mainland and Islands Link Project (Xie et al., 2018). The objectives of this study are: 1) to establish an Island Ecological Vulnerability Index (*IEVI*) to evaluate the ecological vulnerability of island with fixed link to the main land; 2) to predict the change of island ecological vulnerability based on the simulated land use change and tourists change in the next 20 years; 3) to derive the tipping point of island ecological vulnerability to indicate the threshold of anthropogenic disturbance, with the case of Zhujiajian Island; and 4) to provide suggestions on ecological management of based on the threshold of anthropogenic disturbance.

2. Materials and methods

2.1. Study area

Zhujiajian Island is the fifth largest island in China's largest archipelago Zhoushan with an area of about 7000 ha at 122°19′–122°25′ E and 29°49′–29°57′ N. This island belongs to the subtropical monsoon climate and is susceptible to typhoon in summer. The average annual rainfall is 1200–2000 mm. According to the Statistical yearbook of Zhoushan, the island population was 34, 000 in 2015. The terrain is high in the south and low in the north, with many attractive sceneries, such as beautiful beaches, lush forests, distinctive fishing villages and vast seaside baths. The beautiful sceneries on Zhujiajian Island attract millions of tourists every year, while the International Sand Sculpture Festival contributes one third of the tourist population. The construction of airport, sea-cross bridges and ferry terminals largely improved the traffic conditions. Meanwhile Zhujiajian Island is a transit hub for tourists to the Buddhist holy island - Putuo Mountain. The northern part of Zhujiajian Island has become a part of the Putuo Mountain Scenic Spots Group. Local government managers confirmed that over 5 million tourists visited Zhujiajian Island in 2015.

2.2. Data sources

In this study, Landsat-TM images with cloud cover less than 10% between July and September were selected as remotely sensed data sources. The Zhoushan Islands - Main Land Project was completed and opened to traffic in December 2009 (Xie et al., 2018). Based on the study purpose and the traffic open time of the sea-cross bridges, the images of 2010 and 2015 were selected. Images were corrected for geometric distortion in ENVI 5.1. The TM data were geometrically rectified by selecting ground control points and projected into Xi'an 1980 coordinates. The root mean square error (RMSE) among the control points selected on the ground was less than one pixel (Lasanta and Vicente-Serrano, 2012). Based on land use properties in the study area and current land use classification in China, the land-use map was classified into 8 land-use categories: built-up area, farmland, forest land, salt field, ponds and canals, grassland, beach and sea water. Based on the spectral characteristics of different features and field survey data, the interpretation scheme was established, and the remotely sensed data was interpreted interactively. To assist the interpretation, we sampled 25 field survey plots around the island using GPS and sampled 16 accuracy assessment plots in the study area based on Google Earth in the summer of 2015 and 2016 (Fig. 1). According to the field work and Google Earth data, the interpretation precisions were 93.0% (2010) and 92.2% (2015) respectively from the positional accuracy evaluation. The field survey also includes vegetation survey, soil and groundwater environmental quality sampling, visitor questionnaire survey, and interviews with local residents and management departments. Socio-economic data were obtained from annual statistics and the local government.

2.3. Methods

2.3.1. Island ecological vulnerability index

Based on the existing research analysis and the actual situation of Zhujiajian Island, an island ecological vulnerability index (*IEVI*) (Shah et al., 2013; Beroya-Eitner, 2016) was designed to calculate the Island Ecological Vulnerability (IEV). The *IEVI* is calculated from 3 objective layers, using the following formula:

$$IEVI = \frac{E + S}{A} \tag{1}$$

where E is Exposure, S is Sensitivity, and A is Adaptability. The formulas for exposure (E), sensitivity (S), and adaptability (A) are as follows:

$$E = \frac{1}{2}(B_1 + B_2) \tag{2}$$

$$S = \frac{1}{2}(B_3 + B_4) \tag{3}$$

$$A = \frac{1}{4}(B_5 + B_6 + B_7 + B_8) \tag{4}$$

where B_x is the evaluation result of element x, with calculation method in formula (5)

$$B_x = \sum_{i=1}^{n} C_i \times W_i \tag{5}$$

where B_x is the value of the element i, C_i is the single-factor index value, W_i is the weight value of the index i in the factor x, and the weight is obtained by the expert scoring method, and the indexes are shown in Table 1.

According to the “exposure-sensitivity-adaptability” framework (O'brien et al., 2004; Chi et al., 2017; Zang et al., 2017), and the actual situation of Zhujiajian Island, 18 indicators were selected to evaluate the *IEVI* (Table 1). The single-factor index of positive and negative indicators is calculated with formulas (6) and (7), respectively. C_i is a single-factor index value, where RC_i is the actual measurement value of the indicator, and S_i is a standard value determined according to relevant national standards and the actual environmental conditions of the Zhoushan Archipelago.

$$C_i = RC_i/S_i \tag{6}$$

$$C_i = S_i/RC_i \tag{7}$$

Natural pressure (B1) include Influence of disaster (C1), Island area change rate (C2), Coastline change rate (C3) and Steep region proportion (C4). C1 is the frequency of natural disasters in the last five years. The natural disaster frequency is the sum of marine algae blooming and typhoon. The typhoon disaster frequency is derived from the typhoon track forecast system (http://typhoon.zjwater.gov.cn/default.aspx). The number of marine red tide is obtained from the Annual bulletin on the Marine environment of the East China Sea which is released online by East China Sea Branch of State Oceanic Administration (http://www.eastsea.gov.cn/xxgk_166/xxgkml/hytj/dhqhyhjgb/201609/t20160926_8351.shtml).

C2 is the increase rate of island area for the past five years, with calculation method from formula (8)

$$C2_t = (A_t - A_{t-5})/A_{t-5} \tag{8}$$

where $C2_t$ is the increase rate of island area in year t, A_t is the area of island in year t, A_{t-5} is the area of island in year t-5.

C3 is the rate of coastline length change in the past five years, calculated by the following formula:

$$C3_t = (L_t - L_{t-5})/L_{t-5} \tag{9}$$

where $C3_t$ is the change rate of coastline length in year t, L_t is the coastline length of island in year t, L_{t-5} is the coastline length of island in year t-5.

C4 is proportion of slopes greater than 15° in a 100 m × 100 m grid. DEM (Digital Elevation Model) data was used to derive the slopes.

With the development of the island's economy, the contradiction between the supply and demand of land resources will become more exacerbated. Land reclamation is the main solution to supply enough land for development. Under more and more strictly intertidal wetland and coastline protection, it is hard to expand the island area now.

Anthropogenic disturbance (B2) is composed of Population density (C5), Tourism influence (C6), Island development intensity (C7) and Coastline development intensity (C8). C5 refers to the population per square kilometer, C6 is the overlay of distance from the scenic spots, tourist density, and the distance from the Wugongshi ferry terminal, which is the connection point to the holy Buddhist island Putuo Mountain. The number of tourists for different scenic spots supplied by Zhujiajian tourism development investment co. LTD was used in the spatialization of tourist density. C7 means different land types with different development intensity and C8 is the rate between the length of artificial shoreline and natural shoreline. Due to the population management policy C5 is a stable index. After the construction of sea-cross bridge, tourists to this island increased explosively. Meanwhile the island development intensity increased faster than ever. C8 is a stable indicator due to the strict protection of natured coastline.

Net primary productivity (C9) represented the Ecosystem productivity (B3) calculated with Carnegie-Ames-Stanford Approach (CASA) model (Yuan and Bauer, 2007). *NDVI* (Normalized Difference Vegetation Index) was calculated from Landsat-TM images, and the meteorological data such as rainfall, temperature and relative humidity are obtained from monthly reports and historical statistics issued by the meteorological bureau. Environment quality (B4) consists of

Table 1
Assessment indicators of vulnerability of islands.

Objective layer		Element layer	Index layer	Index type		Weight
IEV	Exposure	B1 Natural pressure	C1 Influence of disaster	S	HM	0.34
			C2 Island area change rate	S	HM	0.24
			C3 Coastline change rate	S	HM	0.22
			C4 Steep region proportion	S	HT	0.20
		B2 Anthropogenic disturbance	C5 Population density	S	HM	0.21
			C6 Tourism influence	I	HT	0.22
			C7 Island development intensity	I	HT	0.30
			C8 Coastline development intensity	S	HT	0.27
	Sensitivity	B3 Ecosystem productivity	C9 Net primary productivity	S	HT	1.00
		B4 Environment quality	C10 Groundwater quality	S	HT	0.45
			C11 Soil quality	S	HT	0.55
	Adaptability	B5 Self-regulation ability	C12 Island area	S	HM	0.35
			C13 Island shape complexity	S	HM	0.24
			C14 Plant diversity.	S	HT	0.41
		B6 Social support condition	C15 Resident income	I	HM	0.45
			C16 Resident education level	I	HM	0.55
		B7 Environment conservation	C17 Pollutant treatment capacity	I	HM	1.00
		B8 Comprehensive management level	C18 Management effectiveness	I	HM	1.00

Note: According to the characteristics of the indicators, they can be divided into stable indicators (S) and (I) increasing indicators. Stable indicators can be stable during decades. Increasing indicators can increase rapidly. According to the spatial distribution of the indicators, they can be divided into spatial homogeneous indicators (HM) and spatial heterogeneous indicators (HT). The spatial homogeneous indicators use the same value for the entire study area. The spatial heterogeneous index varies with the spatial location. Delphi method was used to determine the index weights.

Groundwater quality (C10) and Soil quality (C11), which are major environment indicators influencing the island ecosystem. The index of C10 and C11 is calculated with the formula below (Chi et al., 2017):

$$P = \sqrt{\left[\left(\frac{1}{n}\sum P_i\right)^2 + P_{max}^2\right]/2} \tag{10}$$

where P is the comprehensive index of environment quality, n is the number of factors, P_i is the environment quality index of factor i, and $P_{\max}$ is the maximum environment quality index of all factors.

Self-regulation ability (B5) includes Island area (C12), Island shape complexity (C13) and Plant diversity (C14). C10, C11and C14 are derived from the field work during 2015–2016. C14 is calculated with Shannon-Wiener indices (Strong, 2016). Vegetation survey was conducted with 27 vegetation samples in 2016 and used as data source of plant diversity. Landsat-TM images was used to calculated C12 and C13. B6 is collected from annual statistics. Environment conservation (B7) and Comprehensive management level (B8) are estimated from the interviews of local government and experts.

The IEV types are determined with the value of $IEVI$. IEV is divided into five types: non vulnerability ($IEVI \leq 1.0$), marginal vulnerability ($1.0 < IEVI \leq 1.2$), mild vulnerability ($1.2 < IEVI \leq 1.4$), moderate vulnerability ($1.4 < IEVI \leq 1.6$) and severe vulnerability ($IEVI > 1.6$).

2.3.2. Prediction of tourists and built-up area

According to the interview of Zhujiajian Island Tourism Administration Department and the tourism development planning, there will be 10 million tourists in 2020, and 28 million in 2050. Since the growth of tourists will result in less favorable experience, the number of tourist population is predicted with logistic regression (Fig. 2). The maximum built-up land potential in Zhujiajian Island should avoid the following types for construction: 1) slope ≥ 15°; 2) clearance area of airport area; 3) basic farmland area; 4) forest and other specially protected area. The potential area of built-up area is 2754 ha. Due to the limitation of island area, the potential area for built-up land is extremely limited. Therefore, the logistic regression was used to predict the area of built-up area in the next 20 years (Fig. 2).

2.3.3. The simulation of land use map

Based on the results of previous study, 14 driving factors were selected to simulate the future land use map (Xie et al., 2018), which include slope, aspect, distance from the rural road, distance from the main road, distance from the reservoir, distance from the forest, distance from the beach, distance from the built-up area, distance from the farmland, distance from the coastline, distance from the sea-cross bridges, distance from the administrative center, and the influence of tourists. The tourist influence is the overlay of distance from the scenic spots, tourist density, and the distance from the Wugongshi ferry terminal, which is the connection point to the holy Buddhist island Putuo Mountain. Based on the CLUE-S model, the land use in 2015 was simulated based on the land use in 2010. KAPPA test was carried out to compare the simulated results and the actual land use to verify the suitability of selected driving factors and the applicability of the model. Then the spatial distribution of land use changes between 2016 and 2035 was simulated.

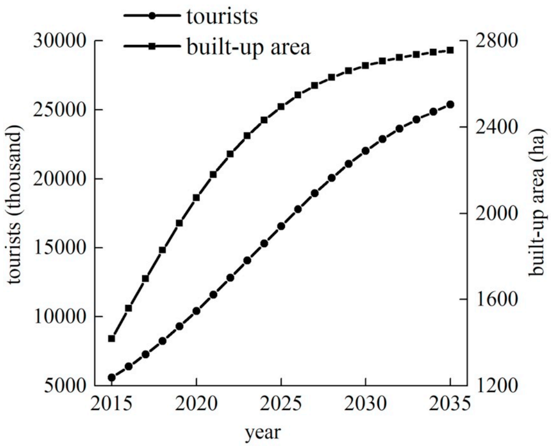

Fig. 2. Logistic regression prediction of tourist population and built-up land.

3. Results

3.1. The ecological vulnerability of Zhujiajian in 2015

According to the $IEVI$ of Zhujiajian Island, the results of vulnerability assessment are shown in Fig. 3 and Table 2. In the north and east of the island the exposure which include natural pressure (B1) and anthropogenic disturbance (B2) is higher than other area, and in the south area the exposure is high but not as serious as in the east. The

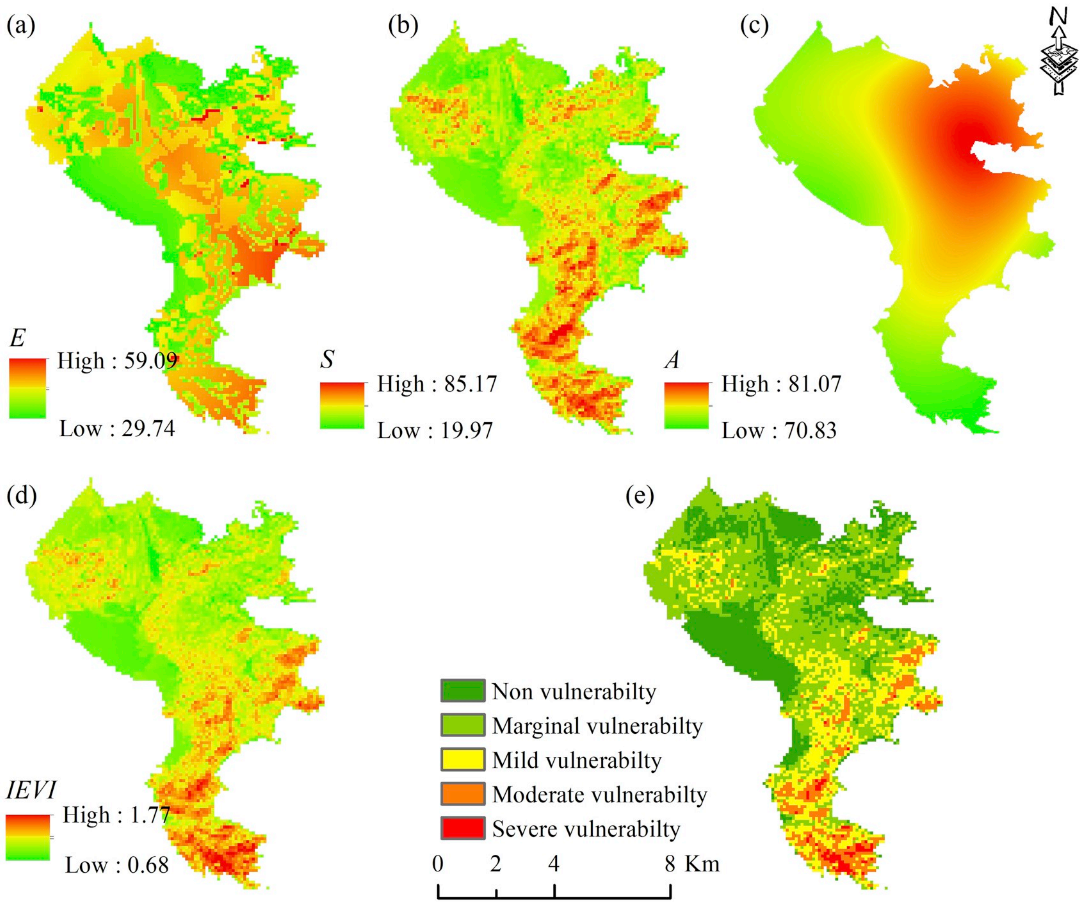

Fig. 3. Ecological vulnerability assessment of Zhujiajian Island in 2015: (a) Exposure, (b) Sensitivity, (c) Adaptability, (d) Island Ecological Vulnerability Index, IEVI, (e) Island Ecological Vulnerability map.

Table 2
The area of different ecological vulnerability type of Zhujiajian Island during 2015–2035.

year	Area (ha)				
	Non vulnerability	Marginal vulnerability	Mild vulnerability	Moderate vulnerability	Severe vulnerability
2015	1784	2821	1508	513	89
2016	1753	2844	1555	519	90
2017	1702	2845	1590	531	93
2018	1650	2833	1635	548	95
2019	1607	2816	1675	565	98
2020	1550	2804	1717	591	99
2021	1511	2774	1756	617	103
2022	1468	2736	1817	636	104
2023	1425	2717	1844	665	110
2024	1392	2691	1876	688	114
2025	1369	2664	1901	707	120
2026	1346	2635	1924	732	124
2027	1328	2598	1942	763	130
2028	1306	2587	1956	778	134
2029	1288	2561	1975	798	139
2030	1279	2539	1983	817	143
2031	1272	2524	1987	833	145
2032	1255	2520	1996	842	148
2033	1245	2513	2001	845	157
2034	1228	2513	2005	858	157
2035	1213	2518	2009	863	158

natural factor such as steep slope is the main driver of exposure that may cause island vulnerability. Heavy anthropogenic disturbance can lead to a high exposure in the northern part of the island. The sensitivity is high in the northern part for the good environment quality and ecosystem productivity in this area. The northeast has high adaptability. The ecosystem of Zhujiajian Island is in relatively good condition now, and the area of moderate (1.33%) and severe vulnerability (7.64%) is small. Meanwhile the severely vulnerable regions are mainly distributed in the southern part. The moderately vulnerable area is distributed in the south and east. More than two-thirds of the island area is in a relative good status include non vulnerability (26.57%) and marginal vulnerability (42.01).

3.2. The simulation of anthropogenic disturbance during 2015–2035

The anthropogenic disturbance mainly includes the rapid increase of tourism influence and island development intensity. The scale of tourism population is forecasted based on the tourism development plan of Zhoushan City and combined with the interview results of the tourism management department of Zhujiajian Island. The explosive growth of the tourists in Zhujiajian Island lead to a rapid increase in economic income which will cause the expansion of built-up area. The land use map during 2015–2035 is simulated by combining the estimation of the maximum potential built-up area and the CLUE-S model.

3.2.1. The simulation of tourism influence during 2015–2035

According to the tickets data of different scenic spots, the proportion of the tourist population at each scenic spot was obtained. The tourism influence was calculated based on the proportion of the tourist population in each scenic spot and the tourists travelling to the Buddhist holy island - Putuo Mountain. The spatial distribution of tourism influence shows that the first-level hotspots is Nansha and Dongsha beaches and the second-level hotspots such as Wushitang, Baishan,

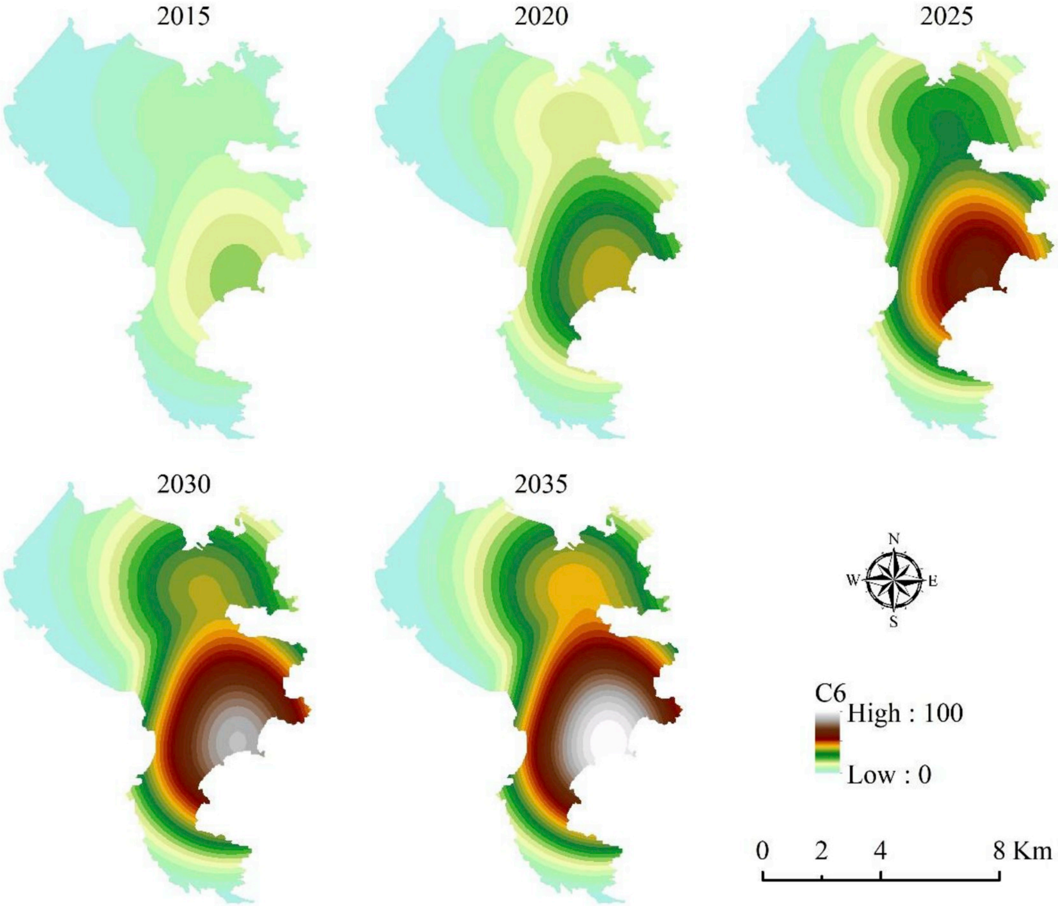

Fig. 4. The prediction of tourism impact of Zhujiajian Island during 2015–2035.

Dadongao and Wugongshi ferry terminal (Fig. 4 and Fig. 1).

3.2.2. *The simulation of island development intensity during 2015–2035*

Based on the simulation of land use in Zhujiajian Island, the island development intensity is simulated during 2015–2035 (Fig. 5). The island development intensity will increase over time. Built-up area will expand around the exit near the sea-cross bridge, the surrounding area of Wugongshi ferry terminal, Dadongao and Nansha scenic spot. The expansion of built-up area in the Daqing Mountain Park is mainly due to the construction of round-island road and the construction of supporting facilities for the increased tourists. The areas with low development intensity are mainly concentrated in steep regions such as Daqingshan, Miaogenshan, and Baishan.

3.3. *The simulation of ecological vulnerability during 2015–2035*

The simulation results indicated that ecological vulnerability of Zhujiajian Island increased during 2015–2035, mainly due to the increase of tourists and the island development intensity (Fig. 6). The severe vulnerability area gradually expanded from Daqingshan in the south to Dongsha, Nansha and other scenic spots. Several severe vulnerability patches appeared around Dadongao which is the township center. Non vulnerable area reduced obviously. Non vulnerable area near the airport, ferry terminal and main road changed to more vulnerable area such as marginal vulnerability or mild vulnerability. In the south, the moderate vulnerability and severe vulnerability area tend to be connected with each other.

The area changes in different ecological vulnerability type of Zhujiajian Island is shown in Fig. 7 and Table 2. The area of non vulnerability and marginal vulnerability decreased by 1/3 and 1/7 respectively, according to the simulation. The area of mild vulnerability increased by 501 ha (33%) during 2015–2035 which ranks the most among the five vulnerability classes. The highest growth rate was the area of severe vulnerability, with an increase of 78%. During 2022–2026, the rate of area change for each type of vulnerability appeared to be the maximum. The decrease rate of low vulnerability area (the sum of non vulnerability and marginal vulnerability) is high during 2021–2023. The vulnerable area (the sum of Mild vulnerability, moderate vulnerability and severe vulnerability) increased quickly during 2020–2026, almost 10% every year. In our hypotheses the island will get nearly 16 million tourists in this period, meanwhile the built-up area will reach 2500 ha, which means the threshold of tourists in Zhujiajian Island is about 16 million per year and the upper limit of built up area is 2500 ha.

4. Discussion

4.1. *The spatial heterogeneity of ecological vulnerability at Zhujiajian Island in 2015*

The severe vulnerable area of Zhujiajian Island is mainly distributed at Daqingshan Mountain in the southern part. The ecological vulnerability simulation showed that the slope can be an inherent factor of island ecological vulnerability (Farhan and Lim, 2012; Kurniawan et al., 2016). The construction of roads used for tourism aggravated the ecological vulnerability means that the anthropogenic disturbance are not merely regulatory factors, but can also be the key factors affecting ecological vulnerability (Bonati, 2014). The moderate vulnerability is mainly distributed in areas with steep topography without roads, or near the scenic spots. The mild vulnerability is mainly distributed in

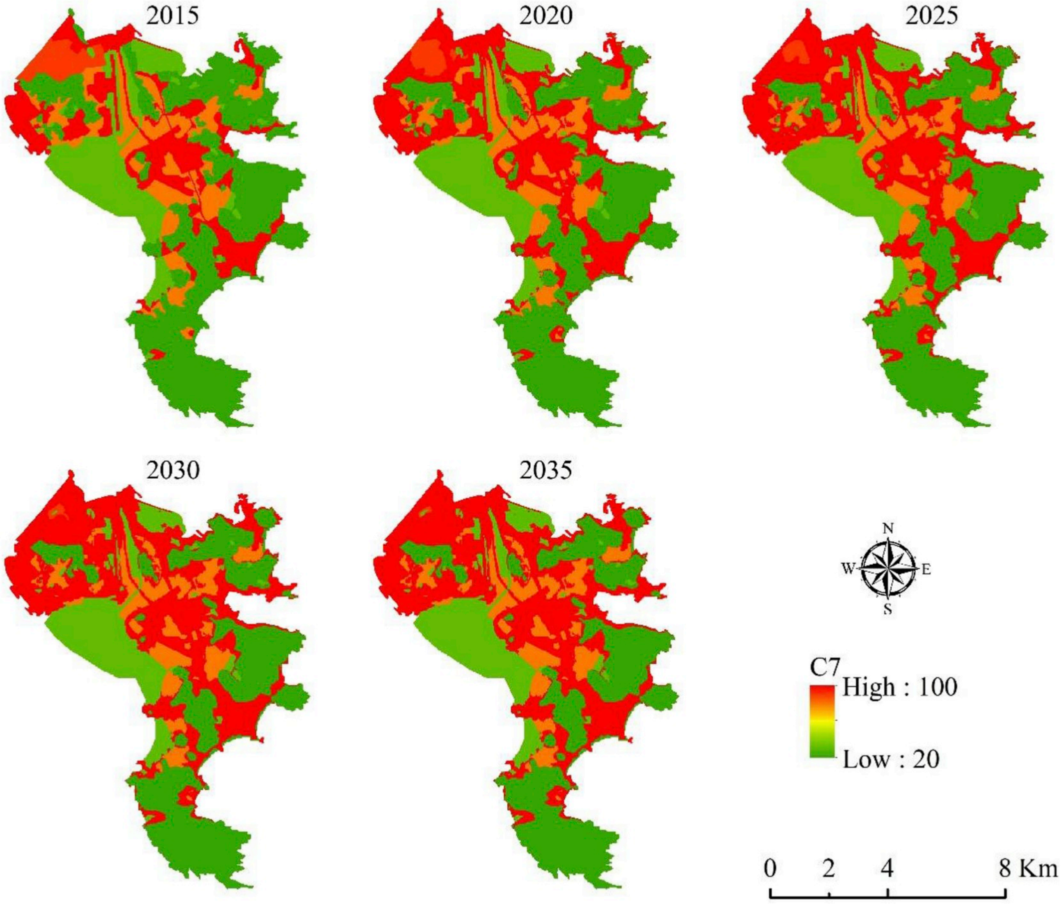

Fig. 5. The simulated development intensity of Zhujiajian Island.

relatively flat terrain, and the built-up areas with dense population. The anthropogenic factors such as population density, tourism influence and island development intensity influenced the ecological vulnerability deeply.

According to the distribution of severe and moderate vulnerability area in Zhujiajian Island, we found that roads are key factors influencing vulnerability. Comparing the moderate vulnerability area with the mild vulnerability area, we found that under similar anthropogenic disturbance, steep area is more vulnerable than flat area. Therefore, natural environment is an inherent factor that contributes to the ecological vulnerability of the island. However, anthropogenic disturbance can be the key factor affecting ecological vulnerability especially with a fixed link to the mainland. For the islands, the anthropogenic activities should be controlled as far as possible in steep areas although those area is not vulnerable at the moment. In the exposure of island, natural pressure (B1) can be an inherent factor for the IEV which is stable during the study period. On the contrary the anthropogenic disturbance (B2) increased rapidly after having a fixed link to the mainland, especially the tourism influence (C6) and island development intensity (C7). Compared with the period before the bridges were constructed, the expansion rate of the built-up area increased by 60% and the number of tourists increased by 135% after being connected with the mainland (Xie et al., 2018). Since the main economic income of Zhujiajain island is tourism, the ecosystem productivity (B3) and environment quality (B4) will be protected in well conditions. The self-regulation ability (B5), social support condition (B6), environment conservation (B7) and comprehensive management level (B8) will eventually determine the adaptability of the island.

4.2. *Threshold of island anthropogenic disturbance*

According to the ecological vulnerability simulation of Zhujiajian Island, with the increase of anthropogenic disturbance, the ecological vulnerability of this island tends to increase, and the severe vulnerability area expands to the surrounding area. A noticeable decrease occurred in the non vulnerability area, especially in the north. During 2022–2026, the rate of area change for each type of vulnerability reached maximum. In our hypotheses the island will get nearly 16 million tourists in this period, meanwhile the built-up area will reach 2500 ha. When the tourists of Zhujiajian Island exceed 16 million, the ecological vulnerability of Zhujiajian Island will be increased significantly. Therefore, under the current social and economic conditions, when the tourism population of Zhujiajian Island approaches the threshold, new policies must be implemented to restrict the number of tourists. Under strict intertidal wetlands and coastline protect policy, it is hard to expand the island area via reclamation anymore. When the built-up area is close to 2500 ha, almost 90% of the potential land for construction will be used. Increasing the intensity of land use in current built-up area will be the only solution to solve the contradiction between the supply and demand of land resources. The prediction of tourists depends on the interview of Zhujiajian Island Tourism Administration Department and the tourism development planning. If the increase of tourists become faster than the perdition in this study, the island will be faced with the risk of more ecologically vulnerable. The increase of built-up area depends on the hypothesis of potential land being used in 2035. Strict land use policy will improve the island vulnerability status (Kurniawan et al., 2016).

Obviously, the mechanisms of IEV are complex, especially the interaction between factors. For example, the change of land use will

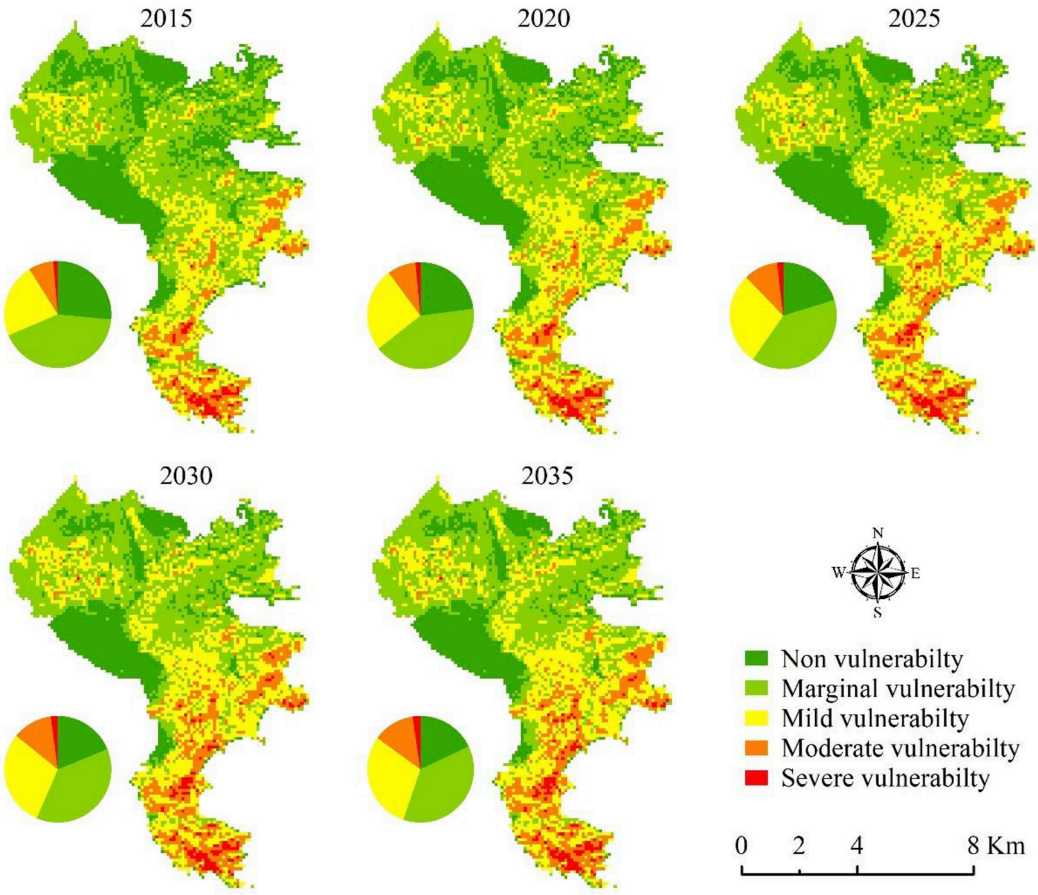

Fig. 6. The simulation of ecological vulnerability of Zhujiajian Island during 2015–2035.

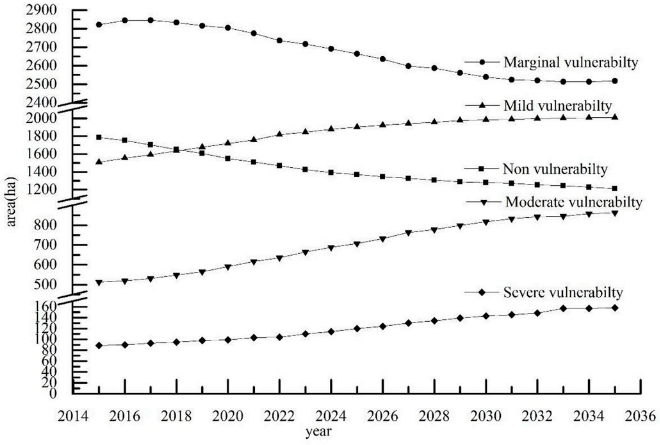

Fig. 7. Changes in different ecological vulnerability type of Zhujiajian Island during 2015–2035.

influence the net primary productivity, groundwater quality, soil quality and plant diversity. Such changes will bring different feedbacks to the IEV. In order to explore the threshold of island anthropogenic disturbance, we hypothesized that other factors remain stable during the study period. Further studies can improve the accuracy of vulnerability simulation by distinguishing the interaction between different factors.

4.3. Suggestions on ecological management of Zhujiajian Island

Ecosystem management is an ecological measure implemented to achieve stable development of ecosystems (Kaufmann et al., 1994). Early ecosystem management measure was mostly based on local resource endowments and experience in ecosystem utilization (Berkes et al., 2000; Tengö et al., 2014), such as obtaining maximum grain, fish, or timber production through ecosystem management (Kessler et al., 1992), especially for fisheries, to maximize the production of a single economic fish (Saenz-Arroyo and Roberts, 2008). Subsequently, based on the climax theory of ecosystem, a management strategy for sustainable and stable production of ecosystems was proposed (Beard, 1944; Holling and Meffe, 1996; Saint-Béat et al., 2015; Varhammar et al., 2015). With the deeper understanding of ecosystems, the proposed multi-stable status theory of ecosystems and the hypothesis of moderate disturbance in ecosystems were proposed (Robbins, 2012). The goal of ecosystem management is no longer limited to the continuous output of a single substance. Due to the complexity of ecosystem functions and the nonlinear response of the system to exogenous and endogenous disturbances (Levin et al., 2013), multi-target ecosystem management tends to be more complicated. The socio-economic activities of human beings as an essential component part of the ecosystem make the management of ecosystems more complicated (Heesterbeek et al., 2015). Based on the vulnerability threshold of tourists and built up area for the island ecosystem, we can improve the effectiveness and pertinence of management strategies for Zhujiajian Island. Since the vulnerability of island ecosystems is influenced by management effectiveness and pollutant treatment capacity, we can reduce the ecological vulnerability by improving management effectiveness and pollutant treatment capacity. Therefore, for islands that are strongly disturbed by anthropogenic activities, especially those islands with fixed link to the mainland, we should formulate serious ecosystem management measures based on ecological vulnerability prediction and anthropogenic disturbance threshold analysis. A reasonable development plan is the guarantee to realize the island sustainable development. The anthropogenic disturbance threshold must be used in the future development planning. The development limit of tourist number should be less than 16 million per year and built-up area should be controlled within 2500 ha.

5. Conclusion

Island Ecological Vulnerability Index *(IEVI)* was used to evaluate the ecological vulnerability of Zhujiajian Island. The ecological vulnerability of island ecosystems is not only a natural property of the island itself, but also a result of strong disturbance from anthropogenic activities. Based on the ecological vulnerability simulation of Zhujiajian Island, we found that the ecological vulnerability of Zhujiajian Island would rapidly increase when 90% of the potential land for built-up area were developed and the number of tourists exceeds 16 million. Therefore, based on ecological vulnerability prediction and anthropogenic disturbance threshold analysis, the area of built-up area and the total number of tourists should be controlled. Meanwhile, improving management effectiveness and waste treatment capacity will reduce ecological vulnerability of the island.

Acknowledgement

This study was supported by Public Science and Technology Research Funds Projects of Ocean (No. 201505012).

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