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Effects of seashore reclamation activities on the health of wetland ecosystems: A case study in the Yellow River Delta, China

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A B S T R A C T

Seashore reclamation is an important way that humans utilize the oceans. In recent years, expansion of seashore reclamation activities has seriously disturbed natural coastal systems, and especially wetland ecosystems. In this paper, using China's Yellow River Delta as a case study, we evaluated the effects of seashore reclamation activities on the health of coastal wetland ecosystems. We defined a comprehensive assessment index system based on the pressure-state-response model and used the model to explore how wetland health responded to reclamation activities, including the construction of tidal embankments and ports, land reclamation, road construction, and upstream dam construction. We found that the pressure intensity index for seashore reclamation activities ranged from 0.39 to 0.77, and increased until the late 1990s. From 1950 to 2010, increasing pressure on the wetlands caused the comprehensive state and health indices to decrease from 0.87 to 0.51 and from 0.64 to 0.52, respectively; both indicate severe risks to ecosystem health. The comprehensive health index decreased continuously until about 2000, then improved. There were strong negative correlations between the comprehensive health and pressure indices and the reclamation activity pressure index (both $R^2 > 0.80$, $p < 0.05$). A sensitivity analysis indicated that the assessment model was robust with respect to the effects of tidal embankment and dam construction. Our results indicate that alleviating the reclamation pressure, especially tidal embankment and dam construction, would significantly improve wetland ecosystem health. Our study will help seashore managers assess the combined effects of existing reclamation activities on coastal wetlands, and support future reclamation activity planning.

1. Introduction

Seashore reclamation is an important way that humans utilize oceans. In recent years, with the expansion of reclamation activities, natural systems in coastal areas, and especially wetland ecosystems, have been suffering from severe disturbance. Reclamation activities have therefore caused habitat degradation, have reduced ecosystem health, and have reduced the services provided by the wetlands to a potentially serious degree. Therefore, it has become important to scientifically assess the effect of reclamation activities and their intensities on the health of wetland ecosystems.

However, most of the previous literature focused on a single aspect of the ecosystem, such as geomorphology (Choi et al., 2007), vegetation (Bi et al., 2014), the macrozoobenthos (Yan et al., 2015), water birds (Yang et al., 2011), and heavy metal concentrations (Ma et al., 2015). The impacts were deduced for a specific kind of reclamation activity (e.g., construction of a dike, port, road, or dam) during a specific period. Spearman et al. (2014) described the potential impact of port deepening on an intertidal habitat, and found that the sediment recycling that was implemented prevented increased habitat loss, and mitigated the subsequent responses of the estuary system to this intervention. Lee and An (2015) investigated *Phragmites australis* distribution patterns in intertidal wetlands of Korea's South Sea and their association with environmental factors in estuaries with and without a dike. Mammides et al. (2015) found that road networks had negative effects on four of the five bird categories they studied at Natura 2000 sites in Cyprus.

Several studies have also considered the comprehensive effect of the intensity of reclamation activity on coastal wetlands, as well as trends in the effect in different periods (Gibson et al., 2007; Yu and Zhang, 2011; Valipour et al., 2015). Li et al. (2009) established

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a qualitative "driver-response" framework for the relationship between reclamation activities and the estuarine environment, but did not quantify the impacts. Zhang et al. (2015) discussed the effect of human activities on the evolution of estuarine wetlands using multi-temporal Landsat remote sensing data, and focused on the change in the wetland cover. In addition, some studies in China's wetlands have been done by developing and applying models, such as a Markov model (Ma et al., 2012a), a system dynamics model (Ma et al., 2012b), and multiple indicators (Ma et al., 2012c). However, there are still some gaps in our knowledge of how to quantify the intensity of various reclamation activities, how to quantitatively evaluate the cumulative effects of expanding reclamation activities (as well as the effects of mitigation efforts) on the comprehensive health of wetland ecosystems, and how to identify the trends in such effects during different periods.

In the present study, our goals were to identify the main indices that describe the impacts of reclamation activities, to establish a comprehensive assessment index system based on the pressure-state-response (PSR) model, and to describe the ecological response of wetlands to reclamation activities and changes in these responses over time. The results will help seashore managers to assess the combined effects of reclamation activities on coastal wetlands, and will support planning of future reclamation activities. To illustrate the use of our method, we chose China's Yellow River Delta as a case study.

2. Study area

The Yellow River Delta (37°35′N to 38°12′N, 118°33′E to 119°20′E) is located on the western coast of the Bohai Sea (Fig. 1), and is the largest and youngest coastal wetland in China. It is one of the most active regions of land–ocean interaction and among the largest river deltas in the world. The region has a temperate, semi-humid, continental monsoon climate. The average annual temperature is 12.1 °C, with monthly means ranging from a minimum of −1.3 °C in December to a maximum of 27.7 °C in August. The average annual precipitation is 552 mm, of which 70% falls during the summer (May to July). However, the average annual pan evaporation is 1962 mm. With economic development in the delta accelerating and urbanization increasing the demand for land, reclamation activities, such as port construction, construction of tidal embankments, aquaculture, land reclamation, and road construction, have expanded continuously. This has greatly increased the pressure on and vulnerability of the Yellow River Delta wetlands. In addition, dam construction in the upstream reaches of the Yellow River has greatly reduced inflows into the estuary, with

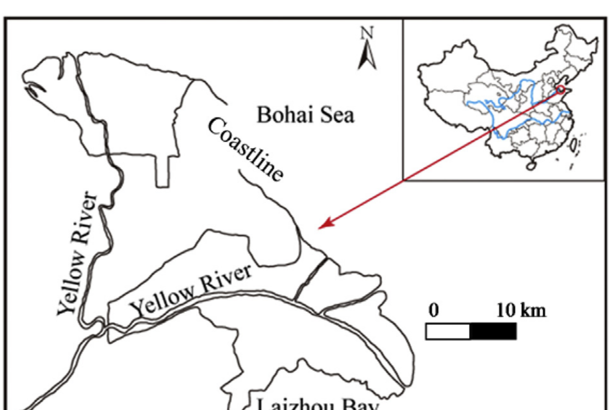

Fig. 1. Map of the wetlands in the Yellow River Delta.

negative impacts on the health of the coastal wetlands. The wetland habitat of the Yellow River Delta wetlands has therefore been suffering from severe disturbance, which has damaged biodiversity (Zhang et al., 2011), and ecosystem structures and functions are facing serious threats (Ottinger et al., 2013).

3. Model establishment

3.1. PSR model

We used the PSR model originally proposed by Rapport and Friend (1979) to analyze the relationships between environmental pressures, the ecosystem's state, and the human responses. The PSR model framework is based on the logic that humans exert a certain *pressure* on the environment, leading to a change in the system's *state*, which is followed by a human *response* to these changes. This model reflects the current state of the ecosystem, identifies the reasons for a change in state, and suggests the response measures required to improve the quality of the environment. As a result, it supports planning and decisions by resource managers, and is a useful tool in coastal ecosystem and coastal area assessment (Ma et al., 2012a; Zhang et al., 2012a, b). In this paper, we introduce a PSR model to assess ecosystem health in the context of reclamation activities in the Yellow River Delta wetlands, with the goal of providing theoretical support for future development of the wetland system.

3.2. Development of a health assessment index system

In this section, we will describe the development of indices that quantify the intensity of each reclamation activity. We will then use the indices to create a comprehensive index that describes the pressure on ecosystem health. The Supplemental Information provides some justifications for our choices of indicators and explanations of their details.

3.2.1. Tidal embankment intensity

Tidal embankments, which are designed to prevent ocean water from moving inland, are the foundation of engineering to support other reclamation activities in coastal areas. The embankments block the exchanges of natural materials and energy between coastal wetlands and the ocean, resulting in shrinkage of the coastal wetlands and disturbing the natural succession processes of wetland vegetation. We developed an index based on the guidelines in China's Code for the Design and Construction of Breakwaters (MOC, 2011) to quantify the intensity of the tidal embankment construction:

$$TEI = \frac{\sum_{i=1}^{n} EI_i}{TL} \tag{1}$$

$$EI_i = L_i \times B_i \times H_i \times (1 + W_i) \times (1 + A_i) \times C_i(1 + \theta_i) \tag{2}$$

where TEI is the tidal embankment intensity index (kN); EI_i is the embankment intensity of segment i of the embankment (kN· m); TL is the total length of the embankment (m); L_i is the length of coastline affected by segment i of the embankment (m); B_i is the width of the levee crown of segment i (m); H_i is the elevation of the top of segment i (m); W_i (dimensionless) is the contribution of parapet walls to the embankment intensity of segment i, with $W \geq 0$ or with $W = 0$ if there is no parapet wall; A_i (dimensionless) is the contribution of protective armor blocks (e.g., riprap) to the embankment intensity of segment i, with $A \geq 0$ or with $A = 0$ if there are no armor blocks; C_i is the strength of the banking soil materials of segment i (kPa); and θ is an opening ratio (i.e., the proportion of