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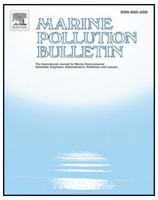

Focus

Development of an integrated indicator system to assess the impacts of reclamation engineering on a river estuary

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ABSTRACT

An integrated indicator system was developed for determining synthetic environmental responses under multiple types of coastal reclamation engineering in the Yellow River estuary, China. Four types of coastal engineering works were analyzed, namely port construction, petroleum exploitation, fishery and aquaculture, and seawall defense. In addition, two areas with limited human disturbances were considered for comparison. From the weights of the response value for each indicator, port construction was determined to be the primary impact contributor among the four engineering works studies. Specifically, hydrodynamic conditions, ecological status, economic costs, and engineering intensity were on average 72.78%, 65.03%, 75.03%, and 66.35% higher than those of other engineering types. Furthermore, fishery and aquaculture impact on water quality was 42.51% higher than that of other engineering types, whereas seawall defense impact on landscape variation was 51.75% higher than that of other engineering types. The proposed indicator system may provide effective coastal management in future.

1. Introduction

Rapid urbanization and industrialization have complicated and significant impacts on the environment and indigenous ecosystems in many coastal regions. The degradation and loss of coastal ecosystems over the past two to three decades have been intense and increasing worldwide (Barbier et al., 2008). Globally, over 40% of the coastal region is heavily impacted by anthropogenic perturbations (Halpern et al., 2008). To meet the increasing and growing demands for resources and land by human beings, coastal areas under rapid exploitation and construction are subject to intensive reclamation activities (Wang et al., 2014). Such activities have many negative effects on ecosystems with varying degrees depending on the reclamation phases and functions (Feng et al., 2014; Wang et al., 2010a), including changes in topographical and hydrodynamic conditions and cascades of consequential impacts upon environmental quality and ecological processes (Naser, 2011; Stefano et al., 2015; Yan et al., 2013). At the same time, the development of coastal reclamation activities, e.g., energy exploitation, fishery and aquaculture, and port construction in estuary areas, are significantly affecting the fate and transport of sands and nutrients, thus greatly altering the water quality. In particular, coastal reclamations have a direct effect on marine ecosystems, especially those in estuary areas that are critical habitats for many important fishery resources (Kirwan and Patrick, 2013; Shen et al., 2016a; Shi et al., 2009). The estuarine regions are also considered typical core areas to promote socioeconomic development in many countries (Barbier and Silliman, 2011; McGlashan, 2002).

The negative effects produced by coastal reclamation activities affect the structures and functions of estuary ecosystems, potentially resulting in wetland shrinkage, coastal line recession, and the occurrence of extreme environmental events (Sun et al., 2015), such as red tide, oil pollution, and habitat loss. Many researchers also stated that a number of engineering works have altered multiple hydrodynamic and topographical conditions and the corresponding ecological responses (Alber, 2002; Wan and Konyha, 2015). For instance, compared to the natural coastline in estuarine regions, sub-base and piling of coastal defense constructions withstand high hydrostatic pressure and net shear stresses originating from the waves and tides (Temmerman et al., 2013), and some even have many concrete dams. This not only increases the risk of storm surge in the associated wetlands but also raises the height of waves and the intensity of vibration period. Furthermore, port construction in coastal regions is producing serious pollution because of the discharge of many contaminants such as sediments and heavy metals and the reduction in eco-compatibility (Liu et al., 2010; Na et al., 2012).

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From another aspect, the landscape structure of coastal wetland ecosystems has been isolated and fragmented after energy exploitation, fishery, and aquaculture. It is not surprising that coastal engineering disrupts the integrity of substance flow in estuarine ecosystems (Elliott et al., 2014; Gedan et al., 2011; Temmerman et al., 2004).

As coastal reclamations have generated sophisticated impacts on estuary ecosystems, which significantly increase the complexity and uncertainty of relevant management activities, understanding the comprehensive response of coastal reclamation engineering and reclamation activities on coastal and estuaries ecosystems is desired. Traditionally, the ecological health indicator system coupled with the pressure-state-response (PSR) framework has been adopted in the Yellow River estuary (YRE), China (Jin et al., 2016). This PSR approach is based on three factors, namely pressure, state, and response, and provides a systematic mechanism to monitor the status of an environment or the sustainable development of natural resources and environmental ecology (Zhou et al., 2013). However, the effects of anthropogenic reclamation activities on many ecological processes in estuaries still have not been fully understood. Few studies have explored and reported the response assessment of multiple engineering types for river estuarine ecosystems. Consequently, there is insufficient data to investigate and analyze the impact pathways of different coastal marine-based engineering and reclamation activities upon ecological and water environment indicators (Maassen and Balla, 2010; Moldan et al., 2012; Singh et al., 2012). Thus, the aim of this study was to propose a comprehensive assessment model of reclamation engineering activities and investigate the potential impacts of such activities on coastal marine environment and ecosystems. Four types of coastal reclamation engineering activities are considered for analyzing the intensities of their environmental influences. Moreover, two reference groups under limited human disturbances (i.e., similar to natural condition) are used for comparison. Furthermore, six clusters of indicators are considered the affecting elements caused by land reclamation activities, reflecting differences in social and natural functional properties. An indicator system will be developed to systematically assess the impacts to provide evidence for the ecological and environmental management of coastal reclamation. This indicators system will enhance the traditional methods that focus on a single aspect of the ecosystem and ignore the impact of coastal reclamation engineering types in terms of (a) determining the responses of coastal environment under multiple types of coastal reclamation engineering, and (b) development of an indicator system for reflecting wetland health, assessing physical fluid mechanics, and managing engineering works.

2. Overview of the study area

Detailed monitoring data and studies on the YRE were collected. The YRE is located in Dongying city, Shandong province of China (36°55′ to 38°16′N and 117°31′ to 119°18′E). The total study area was approximately 2000 km^2, accounting for 43% of the total area of Hekou and Kenli districts, the two local administrative regions in the YRE. The estuary is located in a warm, temperate, and semi-humid continental monsoon climate zone, which is influenced by the Pacific Ocean and Eurasia, which has an unpredictable climate and four distinctive seasons. The quarterly average temperatures are approximately 10.7 °C for March, 27.3 °C for July, 13.1 °C for October, and −5.2 °C for January, respectively. The annual evaporation is 1962 mm, and the annual precipitation is 551.6 mm, with approximately 70% of precipitation occurring over June to August. The mean tidal range is 0.73 to 1.77 m (Sun et al., 2016). Because of soil salinization, major vegetation in the YRE mainly consists of salt-tolerant plants, such as *Suaeda heteroptera*, *Triarrhena sachariflora*, *Tamarix chinensis*, *Phragmites australis*, and *Limonium sinense* (Cui et al., 2009; Jiang et al., 2013). The YRE sediments that are discharged into the sea are mainly composed of silt (8% to 28% of the total) and mud (6% to 21% of the total; Wang et al., 2010b). Moreover, the ecology environment of the region is extremely fragile because of intensive human interventions such as coastal reclamation. In recent years, a number of coastal reclamation projects have been implemented. Compared to the 169.19 km^2 of land used for coastal reclamation over 1982 to 2000, the total reclaimed area was approximately 332.75 km^{2}over 2010 to 2014 in Dongying City (i.e., the home city of the estuary) of Shandong province (Ma et al., 2015). The land reclamation activities have been expanding unceasingly because of increasing demand for land resources. The degradation of coastal ecological environment caused by marine-based reclamation has led to the destruction of benthic habitats (Lee et al., 2014; Zainal et al., 2012), reduction of phytoplankton diversity, variation in aquatic community structure, and succession of the original ecosystem from oceanic to terrestrial (Zainal et al., 2012; Zheng et al., 2011).

In this context, four main types of coastal reclamation in YRE were used as four scenarios for analyzing the impact intensities: port construction (PC), petroleum exploitation (PE), fishery and aquaculture (FA), and seawall defense (SD). Two reference groups, a natural wetland (NW) and river mouth (RM) areas, were considered which were hardly influenced by reclamation activities. As shown in Fig. 1, 18 sampling points were chosen in the YRE, from the north to the south, and distributed in the Dongying Port (DYP), Nature Ecological Reserve of Yellow River delta (NER), Pile no. 5 (NFP), Gudong Seawall (GDS), and Shengli Oil Field (SLOF).

3. Materials and methods

3.1. Modeling framework

Coastal reclamation engineering of shorelines can broadly be categorized into “soft” and “hard” technologies (Lai et al., 2015). The “hard” approach involves physical manipulation of artificial structures such as coastal breakwaters, groynes, piles, ports, and man-made islands. This kind of coastal reclamation usually can meet engineering requirements by changing the shape and size of the marine environment or altering their topographic complexities (Loke et al., 2014). “Soft” engineering mainly includes natural resource exploitation such as FA and energy exploitation, which have the characteristics of occupying less ocean areas and have low intensity of engineering activities. However, the purpose of soft engineering is normally to explore a lot of natural resources, which will introduce cumulative risks to the environment. After considering all the negative environmental impacts, the following modeling framework was proposed (Fig. 2).

3.2. Indicators system

Direct impacts of coastal reclamation engineering on natural coastal environment include changes in the natural coastline length and transformation of coastal wetland areas (Wang et al., 2014), which are the primary causes of many consequential changes. These impacts should be reflected by any indicator system used for impact evaluation. In this study, six clusters of indicators were considered as different impact elements caused by land reclamation activities, reflecting the different social and natural functional properties. Each cluster was called a functional group and included hydrodynamic conditions, ecological status, water quality, landscape variation economic cost and engineering intensity. These indicators covered six main functions affecting the ecological environment in coastal areas. Each functional group was defined as one index (the value ranged from 0 to 1) to reflect the intensity of comprehensive influences. Depending on the proposed fundamental modeling framework (Fig. 2), an assessment indicator system was then established (Table 1). It included

i) Hydrodynamic conditions (FunG-Hdr): the coastal reclamation activities could alter the hydrodynamic environment conditions and result in physical disturbances (Gao et al., 2014). In this research, tidal range and current velocity were considered.

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