Estuarine, Coastal and Shelf Science 170 (2016) 83–90

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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

Drivers, trends, and potential impacts of long-term coastal reclamation in China from 1985 to 2010

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ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form
27 September 2015
Accepted 3 January 2016
Available online 6 January 2016

Keywords:
Coastal reclamation
Urbanization
Coastal economy
Remote sensing
China

ABSTRACT

The reclamation of coastal land for agricultural, industrial, and urban land use—a common worldwide practice—has occurred extensively in the coastal region of China. In recent decades, all coastal provinces and metropolises in China have experienced severe coastal reclamation related to land scarcity caused by rapid economic growth and urbanization. However, the value of coastal wetlands and ecosystems has not been well understood and appreciated until recent development of advantageous methods of restoring reclaimed land to coastal wetlands in many developed countries. The overall objective of this study is to provide detailed spatial and temporal distributions of coastal reclamation; analyze drivers such as coastal economy, population growth, and urbanization; and understand the relationships among the drivers and land reclamation. We used long-term Landsat image time series from 1985 to 2010 in 5-year intervals, in combination with remotely sensed image interpretation and spatial analysis, to map the reclamation status and changes across the coastal region of China. The Landsat images time-series analysis was also conducted to evaluate the effects of the economy, population, and urbanization drivers on coastal reclamation. The analysis results indicated that 754,697 ha of coastal wetlands have been reclaimed across all coastal provinces and metropolises from 1985 to 2010, and the trend increased sharply after 2005. High-intensity coastal reclamation was mainly driven by the booming economy, especially after 2000, associated with urbanization and industrial development in China's coastal region; this was closely correlated with the gross domestic product (GDP) per capita. The continuous large-scale coastal reclamation of its coastal region now means China is facing a great challenge, including the enormous loss of vegetated coastal wetlands, negative environmental effects, and potential disaster risks related to coastal flooding under future change climate conditions. Long-term ecosystem-based coastal protection and management are critical to support sustainable coastal ecosystems in China in the future.

1. Introduction

For centuries, coastal reclamation, including the embanking and filling of coastal wetlands and construction of barriers, seawall, levees, and dikes along the shoreline, has resulted in rapid loss of vegetated coastal wetlands and related environmental impacts, especially in countries lacking land resources. As a result, coastal wetland habitats and ecosystems have been transformed or destroyed by seawalls and revetments. The morphology, hydrodynamics, sediment transportation, and landscape of coastal areas have been impacted or altered (Cearreta et al., 2002; Cheong et al., 2013; Pendleton et al., 2012; Valiela et al., 2001). Many coastal countries, including developed countries such as the USA (Kennish, 2001), Netherlands (Butler, 1972; Hoeksema, 2007), Japan (Suzuki, 2003) and developing countries such as China (Ma et al., 2014; Tian et al., 2008; Wang et al., 2014) and Mexico (Alonso et al., 2003), have conducted coastal reclamation for agriculture, mariculture, industrial use, urban development, and recreation. From the late 1930s to 1980s, the practice of diking coastal wetlands was common for salt hay production, agriculture, recreation, urban expansion, and other purposes along the coasts in the United States (Craig et al., 1979; Templet and Meyer-Arendt, 1988). Now, the scientific community has a better understanding and appreciation of the value of tidal marshes for estuarine and marine wildlife. Since the 1980s, much of the diking action in the USA has been stopped and many of the diked marshes and wetlands have been restored to

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http://dx.doi.org/10.1016/j.ecss.2016.01.006
0272-7714/

tidally functional wetlands as part of long-term sustainable wetland management strategies (Tiner, 2013). In the Netherlands, the embankment and subsequent reclamation of coastal salt marshes started approx. 1000 years ago and culminated during the Zuiderzee and Delta projects of the 20th century. However, protests related to the reduction in wetlands have gradually mounted since the 1960s (Hoeksema, 2007; Wolff, 1992), and land that was once reclaimed has now been restored to tidal wetland for nature conservation to recover its ecosystem functions and services, such as flood protection and healthy marine habitat.

The coastal region in China covers 13% of the nation's territory, hosts 43.5% of the nation's population, and contributes 60.8% of the national gross domestic product (GDP) (Wang et al., 2014). As Chinese coastal areas are among the most densely populated regions in the world, reclaiming land from the sea has become a popular and effective method of managing land shortages and developing the coastal economy. China has a long history of coastal reclamation in river delta areas in relation to coastal defense and has continuously reclaimed coastal wetlands at a large scale for conversion to agricultural, urban, and industrial uses since the 1950s (Temmerman et al., 2013; Wang et al., 2014). Between the 1950s and 1990s, coastal reclamation was aimed at increasing salt, agricultural, and fishery production in China. In recent decades, rapid expansion of the coastal economy and accelerated coastal population growth in China have caused a sharp increase in land reclamation in the coastal region for industry, urban expansion, and infrastructure, which resulted in the cumulative loss of coastal wetlands, negative environmental effects, and a greater risk of potential disasters related to extreme events. Since 1949, approximately 69% of China's mangrove habitat has been lost—only a 151 km^2 area remained in 2012; and approximately 80% of the total area of coral reefs has been lost (An et al., 2007; Zhang et al., 2005). Coastal wetlands in China are now under extremely severe pressure and at great risk of potential threats in terms of marine resources, environmental concerns, and coastal ecology.

In this study, remote-sensing and geographic information system technologies were used to analyze Landsat imagery series data from 1985 to 2010 in 5-year intervals and to determine the reclamation status of coastal regions, as well as the associated changes to spatial distribution across China's nine coastal provinces and two metropolises. To understand how the economy, population, and urbanization affect coastal reclamation, an analysis of temporal and spatial relationships was conducted by qualifying changes in the different levels of development of coastal cities. Thus, this paper aims to answer following questions:

1) What was the status and trend of coastal reclamation in China from 1985 to 2010?
2) How is coastal reclamation driven by economy, demographics, and urbanization?
3) What are the ecological and environmental effects and challenges associated with large-scale and high-intensity coastal reclamation in China?
4) What future coastal management strategies can be implemented to maintain a sustainable coastal environment in China?

2. Methods

2.1. Remote-sensing data and imagery processing

China has more than 32,000 km of coastline, including more than 18,000 km of mainland shoreline and 14,000 km of island shoreline. There are nine coastal provinces (Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan) and two metropolises (Tianjin and Shanghai) in the coastal region of Mainland China, which is bordered to the northeast by the Democratic People's Republic of Korea and to the south by Vietnam.

Landsat, which consists of a series of satellites belonging to the Earth Resource Observation System, offers the longest continuous global record of the Earth's surface. Landsat 5 Thematic Mapper (TM) began receiving imagery data in 1984. The recently launched Landsat 8 Operational Land Imager began collecting imagery data in 2013. Cloud-free Landsat images (216 scenes) of the coastal shoreline in China from 1985 to 2010 at 5-year intervals were collected from Landsat 5 TM and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) at 30 m spatial resolution to evaluate changes in the coastal reclamation of Mainland China (Table 1). The 5-year interval was selected in accordance with China's Five-Year Plan initiatives published since 1953, which provide a series of social and economic development guidelines. The Seventh Five-Year Plan covers the period from 1986 to 1990, and the Eleventh Five-Year Plan covers the period from 2006 to 2010. Because the Landsat 7 ETM + has a data gap related to a failure of the strip with the Scan Line Corrector after May 2003, we applied a de-stripping technique to correct and compensate for the missing Landsat 7 ETM + data by using available Landsat 5 TM data. Landsat 5 TM continues to operate and collect imagery with the same specifications as Landsat 7. Navy nautical charts and digital planimetric maps (1:50,000-scale topographic maps) were used in this study for the geometric correction of remotely sensed imagery data and for the identification and delineation of ancillary data of coastal reclamation.

Image-to-map rectification was performed on Landsat images acquired in 2000 using planimetric maps as the reference maps and a bilinear interpolation resampling method. Edge-matching of the internal ties along the borders of the Landsat source images was also performed using the ERDAS Imagine V9.2 LPS module to obtain a seamless imagery database. Image-to-image registration using a rectified Landsat image in 2000 as the reference image was performed on Landsat images acquired in 1985, 1990, 1995, 2005, and 2010. The overall accuracy of the transformation, which was expressed as the root mean square error for geo-referenced images, was less than 0.5 pixels. After geo-referencing, a bilinear interpolation method was used to rectify and resample the images into the Gauss Kruger Xi'an 1980 coordinate system with the ERDAS Imagine V9.2 platform software package. Because Landsat imagery data were acquired on different dates and under varying atmospheric conditions, the data accuracy was further improved by performing haze reduction and atmospheric correction for all of the multi-temporal scenes using the ATCOR module for ERDAS Imagine V9.2.

2.2. Coastal reclamation analysis

Coastal reclamation analysis requires defining, identifying, and delineating the shoreline to determine alterations of the natural shoreline caused by human interference. Human-altered shorelines, especially bulkhead- and revetment-type seawalls built along the shore with distinctly linear features and high spectral contrast shown on Landsat imagery, were precisely identified, delineated, and manually digitized using the ArcGIS platform. Jetties constructed perpendicular to the coastline with one end attached to the coast were not considered shoreline reclamation (Kumar et al., 2010). The natural shoreline occurs at the intersection of water and land surfaces, and its detection by automatic and manual digitization techniques is complicated by water-saturated zones in the vicinity of the land-water boundary as well as by different coastal demographics and landforms (Boak and Turner, 2005). We used proxy shoreline features, such as the edge line of vegetation and dune toe, to semi-automatically identify and delineate the natural