Estuarine, Coastal and Shelf Science 202 (2018) 290–301

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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

Coupled hydrodynamic and ecological simulation for prognosticating land reclamation impacts in river estuaries

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ARTICLE INFO

Article history:
Received 17 August 2017
Received in revised form
28 November 2017
Accepted 18 December 2017

Keywords:
Hydrodynamic simulation
Phytoplankton
Growth suitability index
Coastal reclamation
Coastal engineering
River estuary

ABSTRACT

A multiphase finite-element hydrodynamic model and a phytoplankton simulation approach are coupled into a general modeling framework. It can help quantify impacts of land reclamation. Compared with previous studies, it has the following improvements: a) reflection of physical currents and suitable growth areas for phytoplankton, (b) advancement of a simulation method to describe the suitability of phytoplankton in the sea water. As the results, water velocity is 16.7% higher than that of original state without human disturbances. The related filling engineering has shortened sediment settling paths, weakened the vortex flow and reduced the capacity of material exchange. Additionally, coastal reclamation lead to decrease of the growth suitability index (GSI), thus it cut down the stability of phytoplankton species approximately 4–12%. The proposed GSI can be applied to the management of coastal reclamation for minimizing ecological impacts. It will be helpful for facilitating identifying suitable phytoplankton growth areas.

1. Introduction

A river estuary is an inland area that has a connection to an ocean. Such estuaries are normally intersection regions between fresh and salty water, and are critical habitats for many precious ecosystems. Due to biodiversities caused by the mixture of river and ocean ecosystems, as well as the intersection of many geographic, chemical, physical and environmental conditions, estuarine regions can provide diverse habitats for many animals, plants, and phytoplankton. Thus it is appropriate for forming complicated and critical water-ecology systems (Sin et al., 2015). Estuaries are also key areas to economic development in many countries, and are thus subject to intensive human disturbances, posing potential risks to local ecosystems.

Over the past decades, rapid urbanization and industrialization have been occurring in many coastal areas across the world (Qiang, 2014). In order to satisfying with the increasing demands for coastal land use, the coastal reclamation engineering have become an important anthropogenic activities in coastal areas (Kirwan et al., 2013). However, the coastal reclamation activities have many negative effects on ecosystems, especially for the contradiction between economic development and habitats protection for indigenous ecosystems is serious in estuarine region (McGlashan, 2002; Orseau et al., 2017). Coastal reclamations are thus of increasing concerns due to the change of topographical and hydrodynamic conditions, as well as cascades of consequential impacts upon phytoplankton and ecosystems (Naser, 2011; Xu et al., 2017a). For example, many of artificial structures constructed by coastal reclamation activities (including port, seawall, oilfield and artificial islands) can cause the shrinkage of a large area of coastal wetlands (Jiang et al., 2017; Teka et al., 2012), which are usually considered as the potential habitats for coastal species (Perkins et al., 2015; Jiang et al., 2015). Furthermore, the loss of habitats will indirectly lead to the reduction of biodiversity and destruction of ecosystem stability in coastal areas (Malm et al., 2004; Agboola et al., 2016). Among many activities associated with coastal reclamation, a lot of scholars believe that hydraulic fill engineering is a major reason to impact habitats connectivity (Qiang, 2014; Olden and Naiman, 2010). Additionally, dredging engineering in the Patía River delta can periodically affect the survival of the associated mangrove trees partly due to alteration of sea levels or salinity (Restrepo and Cantera, 2013). River drainage engineering is positively correlated with species densities for sole larval species (Vinagre et al., 2007). Therefore, it is desired to investigate and

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https://doi.org/10.1016/j.ecss.2017.12.009
0272-7714/

analyze impact pathways of human related activities upon topographical and hydrodynamic conditions, as well as the corresponding ecological responses, which is of great importance to balance economic development and ecosystem conservation.

Previously, many studies were undertaken for analyzing impacts of human activities upon various ecosystems in many areas including estuaries. The previous study have evaluated effects of changes in flow and water velocity, which will affect external environmental conditions for many aquatic creatures. For example, Chambers et al. (1991) stated that water flow was a major physical variable that affected the habitat suitability and dispersal pattern for phytoplankton, compared to the nutrient concentration and temperature impact the growth of species. In the Danube River, biomass of aquatic plants peaked at flow velocity around 0.3 m/s. At the same time, a low biomass was observed for the dominant phytoplankton mosses when the flow velocity was greater than 0.7 m/s (Janauer et al., 2010). Manolaki and Papastergiadou (2013) believed water flow velocity was a critical parameter that could disturb nutrient structure in water and thus affect stability of ecosystems. Many researchers argued that there exist a optimal flow range providing suitable physical conditions for aquatic individuals' growth and dispersal dynamic (Anderson et al., 2013; Hogan et al., 2016; Larsson and Jonsson, 2006; Seenath et al., 2016). Water flow that was lower than the lower bound of the range would lead to a low rate in encountering suspended food particles, caused the reduction of growth rate for aquatic species. Similarly, water flow that was higher than the upper bound of the range would lead to a low efficiency in capturing suspended food particles (Grizzle et al., 1992; Ackerman and Nishizaki, 2004). A few studies reported that water velocity was responsible for the spatially correlated distribution of shellfish densities (Olli and Trunov, 2010). According to the study of biological toxicology, when the optimal hydrodynamic conditions existed, the suitable growth of *Synechogobius hasta* appeared to be triggered by a combination of optimal temperature (i.e., 25 °C ± 0.02) and available nutrients (Liu et al., 2011). However, most of ecological modeling studies focused on macroscopic behaviors of species or systems with ecological significance. On the other hand, traditional research on water hydrodynamics paid much attention to physical processes based on multiple microcosmic physical mechanisms (Jonathan et al., 2008). Investigation of water ecological prognostication in connection with specific phytoplankton species based on hydrodynamic process simulation were scarcely reported.

Coastal reclamation in river estuaries is especially intensive due to the rising demands for land resources to support high-speed economic growth in China. Since the implementation of the “Registration of Coastal Land Use Permits” over 1993 to 2013, the cumulative reclamation areas have reached 1742.38 km^2. The majority of the reclaimed lands are located in the river deltas and estuaries. For example, the Yellow River estuary in China especially has rich nature resources. At the same time, it is the important space for the culture of *Apostishopus Japonicas*. The high intensity of coastal reclamation activities (such as estuary damming and manmade island projects) will induce the degradation of the ecological environment (Zhang et al., 2012), which may consequentially lead to the irreversible destruction of local ecosystem (Newell et al., 1998; Watling, 1975). Spatial and temporal variations in water dynamics induced by human reclamation could result in colonization of sediment deposition and river diversion (Carus et al., 2017; Cozzoli et al., 2014, 2017; Li, 2010; Wang et al., 2010). According to pervious study, coastal reclamation have a greatly effect on water flow (Bornette and Puijalon, 2011). Because of water depth variation (Qin et al., 2014) and coastline migration (Kleinod et al., 2005), the beneficial habitat and biodiversity will be reduced or lost (Yang et al., 2010). However, the effects of anthropogenic reclamation activities on the ecological process in estuaries still have not fully understood. Few studies exploring the inner linkage between water hydrodynamics and ecological processes have been reported in these areas (Fonseca et al., 2002; Rogers et al., 2017; Wal et al., 2017).

In this paper, we test the hypothesis of changes in phytoplankton communities as response to changes in hydrodynamic. The phytoplankton is considered as a new fluid phase in the model, which is moved along with water flow. Here, the water environment is regarded as a single and homogeneous system (light and nutrients are replete). We have ignored other environmental factors impacted on phytoplankton (such as salinity and tide), considered the influence of hydrodynamic conditions on habitat suitability, and acquired the potential species dispersal pathway (More detailed assumptions see the 3.4 section). For this purpose, this research is to investigate and analyze impacts of changing flow velocities on growth suitability for local phytoplankton due to coastal reclamation. About two scenarios, including original condition and after coastal reclamation activities are involved in simulation processes, which can be used as a contrast to analyze the variation of flow field under coastal reclamation activities. In the process of simulation, a multiphase finite-element hydrodynamic and phytoplankton growth simulation approach (MEHD-AGSA) will be coupled into a general modeling framework. This approach will enhance traditional methods which focused a single aspect of hydrodynamic variation and ignored the effect on potential habitat suitability and simulate responses of ecosystems towards changing aquatic environmental conditions. In detail, the following tasks will be tackled: i) the utilization of a hydrodynamic model to describe impacts of land reclamation activities on hydrodynamic conditions, ii) the advancement of a growth suitability index (GSI) to help calculate the degree of aquatic ecological stability under the influence of the hydro-physical disturbances. Through utilizing the distribution of critical velocity gradient to identify suitable growth areas for specific species, GSI coupled the physical field can be used, which would have high ecological implications, and iii) application of the proposed method to evaluate the corresponding variations in GSI of two typical phytoplankton species. In general, this research have described that (a) the reflection of physical currents and suitable growth areas for multiple phytoplankton species, (b) advancement of a simulation method to describe the suitability of phytoplankton in the sea water under changing environmental conditions, and (c) the demonstration of the proposed approach in a studying case that will be based on conceptualization of a practical problem in the Yellow River delta. The results can be applied to the management and design of coastal reclamation plans to minimize ecological risks. This will also be helpful in facilitating identify suitable growth areas for aquatic species under physical disturbances.

2. Overview of the studying case

In this research, a conceptualized case is established based on real-world data and information of the Yellow River estuary (36°55′–38°16′N, 117°31′–119°18′E). The estuary is located in the warm temperate semi-humid continental monsoon climate zone. It is influenced by Pacific Ocean and Eurasia, with a high precipitation (530–630 mm) in summer, enjoying a wild climate and four distinctive seasons. The annual mean temperature ranges from 11.5 to 12.4 °C (Sun et al., 2014a,b). The extreme maximum temperature is 41.9 °C, and the extreme minimum temperature is −23.3 °C. Approximately 68% of the total annual precipitation occurs in the summer time (Fang et al., 2005). The sediments in the estuary are silt-dominant, consisting of more than 73% silt (the grain size of particles range from 0.005 mm to 0.05 mm) and 14% clay (the grain