Journal of Hydrology 529 (2015) 1562–1577

Contents lists available at ScienceDirect

Journal of Hydrology

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

Hydrology, sediment circulation and long-term morphological changes in highly urbanized Shenzhen River estuary, China: A combined field experimental and modeling approach

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ARTICLE INFO

Article history:
Received 1 September 2014
Received in revised form 18 March 2015
Accepted 14 August 2015
Available online 20 August 2015
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Nicolas Gratiot, Associate Editor

Keywords:
Sediment circulation
Morphological process
Hydrographic survey
Long-term simulation
DELFT model
Rapid urbanization

SUMMARY

The Shenzhen River estuary is a small estuary in highly urbanized regions between Shenzhen and Hong Kong, China. An increasing amount of sediment has been observed to accumulate in the estuary, imposing a severe impact on the ecological environment. In this study we utilized a series of hydrographic and bathymetry surveys to study the hydrology, sediment transport and morphological processes in the estuary. Flow and sediment circulation patterns in different seasons were inferred using current velocity, salinity and suspended sediment concentration (SSC) time series collected in the hydrographic surveys in conjunction with fathometer profiles in bathymetry surveys. Historical time series at two stations were also analyzed by Mann–Kendall test for possible trends of the driving forces for estuarine morphological processes. The two-dimensional depth-averaged DELFT numerical model was employed to simulate the flow, salinity and SSC fields during the synchronous surveys and to predict the long-term morphological processes in the estuary. A bimodal SSC distribution was observed with two high-SSC zones separated by a low-SSC zone near the central bay, which cannot be explained by the conventional nongravitational transport theory of Postma (1967). It is hypothesized that sediment circulation in the estuary can be separated into two different systems: the "tidal zone" is under the influence of marine sediment from the Pearl River estuary, whereas the "fluvial zone" is mainly affected by terrestrial sediment from the river. Sediment mass exchange between the two systems is limited due to the presence of the low-SSC zone, the location of which could vary with the relative strengths of river flow and tides. The trend analysis of historical time series shows that the river discharge and the mean sea level are increasing and the flood tide range and the ebb tide range are decreasing. These trends are closely related to the intense human activities in the urbanization of Shenzhen. The long-term simulations show depositional trends for the inner bay and the coastline of the outer bay, which could be further aggravated by the detected trends of the driving forces.

1. Introduction

Sediment deposition is one of the major environmental concerns for estuaries. Due to channel widening and saline intrusion, sediment particles are prone to settling in estuaries, and severe sediment deposition is frequently observed. Heavy sediment deposition may cause significant morphological changes, which in turn alter the ecological environment of the estuary. Furthermore, deposited sediment once contaminated by polluted water becomes a potential source of hazardous chemicals when surface water quality is restored. Sediment deposition in an estuary can be highly variable when the estuary is strongly disturbed by certain factors, such as land reclamation in the estuary or other human activities in its catchment.

The Shenzhen River estuary experienced severe sediment deposition in recent decades. The estuary lies on the boundary of Shenzhen and Hong Kong, and is connected with the South China Sea via the Pearl River estuary. Two important nature conservation sites are located at the river mouth in the estuary: Futian Mangrove-bird Nature Reserve, one of the few mangrove sites in China, is located on its north side and Mai Po Marshes Nature Reserve, a RAMSAR site declared in 1995, is located on its south

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http://dx.doi.org/10.1016/j.jhydrol.2015.08.027
0022-1694/

side. Since the late 1970s, Shenzhen has experienced rapid growth in its population and economy. Permanent residents in Shenzhen increased from 0.37 million in 1981 to 10.55 million in 2012 and the Gross Domestic Product increased from 0.5 billion RMB in 1981 to 1295.0 billion RMB in 2012 (NBSC, 2012). At the same time, large volumes of sediment have been observed to rapidly accumulate in the estuary. Shenzhen and Hong Kong have launched a series of regulation projects to remediate sediment deposition in the estuary. Hydrographic surveys have been carried out regularly in order to explore the hydrology and sediment transport in the estuary since the 1990s. However, few studies have been reported in the literature for this region.

Sediment transport and related morphological processes in estuaries have long been investigated by scientists and coastal engineers (Carling, 1982; Harris and Collins, 1984; Fenster and FitzGerald, 1996; Woodruff et al., 2001; Uncles and Stephens, 2010, among others). Several surveying techniques, including hydrographic surveying, sonar scanning, field sampling and sediment coring, were widely used in estuarine field studies. For example, Carling (1982) measured current and wave dynamics, sediment properties, SSC and sedimentation rates at fixed stations to study their temporal and spatial variations, and discussed the links between sediment resuspension and sedimentation rates for an intertidal zone in South Wales. Fenster and FitzGerald (1996) used several types of survey data including fathometer profiles, side-scan sonograms, hydrographic data, seismic profiles and bridge borings to synthetically study the sediment circulation and its morphological responses in the lower Kennebec River estuary in the USA. The SSC distribution in an estuary is often characterized by the existence of a "turbidity maximum", where the SSC is significantly higher than that in the upstream and downstream regions. Although several theories have been proposed for the formation of turbidity maximum (Postma, 1967; Festa and Hansen, 1978; Simpson et al., 1990; Stacey et al., 2001; Lerczak and Geyer, 2004; Burchard and Hetland, 2010; Ralston et al., 2012; Geyer and MacCready, 2014), it remains a difficult task to clarify the estuarine sediment circulation pattern due to its complex nature. Intensive data have been collected from the hydrographic and bathymetry surveys performed in the Shenzhen River estuary, thereby offering an excellent opportunity for studying the hydrology, sediment transport and morphological processes.

When investigated on a larger time scale, field data might not be sufficient for small estuaries with short survey histories such as the Shenzhen River estuary. Under such circumstances, numerical models can be used as a supplementary tool in analyzing the long-term processes. Attempts to investigate the sediment transport and morphological processes with numerical models have been made in a variety of studies of different time scales (for example, see Cao et al., 2002; Wu, 2004; El kadi Abderrezzak and Paquier, 2009; Chen et al., 2010; Zhang and Duan, 2011; among others). These models, sometimes called "process-based" models because they solve coupled systems of hydrodynamic equations and sediment transport equations, successfully reproduced the fluvial processes in event-based simulations. However, quantitative predictions of morphological processes on larger time scales such as years or decades remain a challenging task for several reasons: (1) the computational time steps in process-based models are usually limited to a few minutes or even seconds due to stability consideration; (2) the error accumulation effect causes the model results to deviate from true solutions; (3) morphological changes are often in response to extreme events which are stochastic; and (4) morphological evolution may be chaotic in nature. Nonetheless, recent studies (Cayocca, 2001; Lesser et al., 2004; Seybold et al., 2009; Mariotti and Fagherazzi, 2010) using numerical models in long-term morphodynamic simulations showed promising results, encouraging the use of a numerical model in exploring the long-term morphological processes in the Shenzhen River estuary. The DELFT model developed by DELTARES (previously known as Delft Hydraulics, Lesser et al., 2004) has been proposed in many studies (Lesser et al., 2004; Dastgheib et al., 2008; Van der Wegen et al., 2011), and is used in the present study.

This paper presents the work carried out in recent hydrographic and bathymetry surveys in the Shenzhen River estuary. The objective of this study is to analyze the flow and sediment circulation pattern in the Shenzhen River estuary with recent survey data, and to predict the long-term trends of sediment deposition under different scenarios of driving force variations. The Shenzhen River estuary presents some unique sediment circulation patterns not possessed by other estuaries reported in the literature. Furthermore, intense human activities in the urbanization could seriously affect the river flow and tidal dynamics in the estuary, which may impose potential adverse impact on the estuarine morphological processes. The present study may help to understand the source and formation mechanism of sediment deposition in small urbanized estuaries with similar settings as the Shenzhen River estuary and to find possible solutions to control the estuarine sediment deposition.

2. Physical setting of the Shenzhen River estuary

The Shenzhen River estuary consists of the main stream of Shenzhen River and the entire Shenzhen Bay (Fig. 1). Shenzhen River is an urbanized tidal river connecting to the Pearl River estuary via Shenzhen Bay. The total length of Shenzhen River is 33 km, and the channel under tidal influence extends from the river mouth to about 13 km upstream. Major tributaries of Shenzhen River include Buji River, Futian River, Huanggang River, Xinzhou River, Wutong River, Shawan River and Liantang River (Dasha River and Yuen Long River flow directly into Shenzhen Bay). A summary of the tributaries are listed in Table 1. The catchment of Shenzhen River locates on the south of the heavily populated Pearl River Delta, covering a drainage area of 312.5 km^2, with 187.5 km^2 in Shenzhen (Chan and Lee, 2010). The northern (Shenzhen) side and the southern (Hong Kong) side of the catchment are distinctively different. On the north of the Shenzhen River it is primarily urbanized areas and on the south it is rural villages and wildland with relatively population density. The catchment has a warm and humid subtropical maritime monsoon climate, and the average annual rainfall between 1995 and 2009 is 1998.4 mm, producing an annual stream volume of 530×10^6 m^3, with over 85% occurring between April and September. Shenzhen Bay is located between latitudes 22.41°N and 22.53°N, longitudes 113.88° E and 114.00°E. It is 13.9 km long and between 4 and 8 km wide, covering an area of 85 km^2. The mean water depth is only 2.9 m in the inner bay and increases to over 7 m in the outer bay. The suspended sediment and the bottom sediment in the estuary are within the range of cohesive silt and clay, with coarser particles occasionally found near the bay mouth and river mouth. The Municipal Shenzhen River Regulation Office of Shenzhen measured the particle size distributions at a number of sites in the estuary (unpublished data), and found that the median sizes were 8–15 μm for suspended sediment and generally below 32 μm for bottom sediment. The tides in the estuary are semidiurnal with an average range of 1.4 m. Rapidly deposited sediment may gradually decrease the environmental capacity of the Shenzhen River estuary, which becomes a potential threat to the ecosystem in aquatic systems.

3. Data and methods

3.1. Data source

Survey data to be analyzed in the present study were summarized in Table 2. Three types of surveys were conducted by the