Continental Shelf Research 66 (2013) 19–28

Contents lists available at SciVerse ScienceDirect

Continental Shelf Research

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

Hydrodynamics in the Yellow River Estuary via radium isotopes: Ecological perspectives

Bochao Xu [a,b], William Burnett [c], Natasha Dimova [d], Shaobo Diao [e], Tiezhu Mi [b], Xueyan Jiang [a], Zhigang Yu [a,*]

[a] *Key Laboratory of Marine Chemistry Theory and Technology, Ministry of Education, Ocean University of China, Qingdao 266100, China*
[b] *Key Laboratory of Marine Environment and Ecology, Ministry of Education, Ocean University of China, Qingdao 266100, China*
[c] *Department of Earth, Ocean and Atmospheric Sciences, Florida State University, Tallahassee, FL 32306, USA*
[d] *Department of Geological Sciences, University of Alabama, Tuscaloosa, AL 35406, USA*
[e] *Qingdao Institute of Marine Geology, Qingdao 266071, China*

ARTICLE INFO

Article history:
Received 25 March 2013
Received in revised form
20 June 2013
Accepted 24 June 2013
Available online 4 July 2013

Keywords:
Submarine groundwater discharge
Water age
Radium isotopes
Ecological response
Nutrient budget
Yellow River Estuary

ABSTRACT

We used radium isotopes as tracers to characterize coastal hydrodynamics and submarine groundwater discharge (SGD) in the Yellow River Estuary in order to assess the ecological effects in one of the most turbid estuaries in the world. Based on apparent water ages calculated by ^{224}Ra/^{223}Ra activity ratios, we found that the river plume flowed mainly southeast at a flow rate of 5–7 km d^{-1}, while a small portion of the river plume was diverted northeast to the central Bohai Sea at a flow rate of less than 2 km d^{-1}. We estimate that with this flow regime, nutrients would be consumed within about two weeks mostly by microplankton and nanoplankton near shore, and picoplankton further offshore to support an average primary production of 0.14 g C m^{-2} d^{-1}. We then used a ^{226}Ra mass balance model to quantify the SGD flux in the study area. The estimated SGD flux was 1.3×10^9 m^3 d^{-1} with a range of 2.8×10^8–3.0×10^9 m^3 d^{-1}. Even the minimum SGD value was about 3 times higher than the Yellow River discharge at that time. The SGD input of dissolved nutrients was shown to be very important to the estuarine nutrient budget, at least 5 times higher than river input. Sediment regeneration of nutrients proved to be very small relative to the SGD flux in this region.

1. Introduction

Estuaries play an important role in the transportation and transformation of terrestrial material carried by rivers, which eventually is mixed into coastal margins (Lohrenz et al., 1990; Dagg et al., 2004; Swarzenski et al., 2006). Many estuarine systems are contaminated by anthropogenic inputs due to rapid economic development and urbanization processes. In addition to surface inputs, contaminants may enter the local aquifer system and are transported via groundwater to coastal areas. Because of the ubiquitous nature of submarine groundwater discharge (SGD) along many coastlines, it has been recognized as one of the most important pathways that may directly affect estuarine ecosystems and geochemical budgets (Johannes, 1980; Moore, 1996; Corbett et al., 1999; Charette et al., 2001; Burnett et al., 2006). Specific local hydrodynamic characteristics such as water transport rate will control the fate of components within water bodies and determine whether these materials will reside long enough to affect the biogeochemical processes in the coastal system (Rapaglia et al., 2010). Thus, quantification of the SGD flux and water transport rate are important for resource managers to evaluate the environmental conditions.

Naturally-occurring U/Th isotopes have drawn coastal oceanographers' attention for their effectiveness in examining water mixing and SGD processes in the coastal zone. Radium isotopes are the main tracers employed in this work as they have been shown to provide useful information concerning mixing and advection (Moore, 1996, 2000a, b; Krest et al., 2000; Kim et al., 2003; Hwang et al., 2005; Dulaiova and Burnett, 2008; Peterson et al., 2008a; Zhang et al., 2011; Gu et al., 2012). Because their half-lives are very different (from days to thousand years), suitable isotopic combinations have the potential to examine complex coastal dynamics over various time scales. In a river-estuary-coastal zone continuum, hydrological processes are typically on timescales of days to weeks. Thus, short-lived ^{224}Ra ($t_{1/2}=3.66$ days) and ^{223}Ra ($t_{1/2}=11.4$ days) can serve as useful geochemical "timers" to evaluate water flushing ages. Over this time scale, radioactive decay does not significantly affect the activities of the long lived ^{226}Ra ($t_{1/2}=1600$ years) or ^{228}Ra ($t_{1/2}=5.8$ years), so

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[*] Corresponding author. Tel.: +86 532 66781006.
E-mail addresses: zhigangyu@mail.ouc.edu.cn, zhigangyu@ouc.edu.cn (Z. Yu).

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http://dx.doi.org/10.1016/j.csr.2013.06.018

they could be used to normalize the short lived radium isotopes to minimize the effects of non-conservative behavior (Moore, 2000a).

The Yellow River is the second longest river in China. The river flows over 5400 km, draining an area of 745,000 km^2 before entering the Bohai Sea at Lijin, in Shandong Province. The mouth of the Yellow River is located between the Bohai Bay and Laizhou Bay, and has an average tidal range of 0.5–1.5 m (Jiang et al., 2007). The Yellow River Estuary is a typical littoral wetland ecosystem with large biological resources, and it serves as an important migration station, wintering habitat and breeding farm (Wang et al., 2009). However, the discharge of the Yellow River has significantly decreased since the 1950s due to both climate change and human activities. Remediation was begun at the beginning of the 21st century with the so-called Water-Sediment Regulation Scheme (WSRS) implemented by the Yellow River Conservancy Committee (YRCC). In this procedure, a large controlled release of floodwaters from the Xiaoliangdi Reservoir (~870 km upstream of the mouth) was used to scour the lower reaches of the river within 10–20 days (Wang et al., 2010a). As a result of this initiative, unusually large amounts of sediment were delivered to the coastal region in a short time and deposited at the river mouth forming a cluster of sand bars. A previous study showed how the river plume pathway meanders significantly across these sand bars (Wang et al., 2005). Therefore, in order to understand the actual direction of the Yellow River plume, high density sampling should be performed.

It has been found before that biological activity (i.e., bioturbation) of coastal areas, such as irrigation of burrows dug by crabs and worms, could significantly enhance groundwater discharge (Miller and Ullman, 2004; Moore, 2006). Such bioturbation activities on the Yellow River Estuary coast are very well pronounced. Chen et al. (2007a), for example, found more than 22 crab burrows per square meter along this shoreline. The typical burrows penetrate 30 cm deep with a diameter of 5.5 cm. During flood tide, estuarine water fills the crab burrows transporting terrestrial/marine materials into the sediment and promoting exchange with deeper pore waters. During ebb tide, water from the burrows is found to discharge back into the estuary. We hypothesize that because of the large number of burrows, this mechanism plays a significant role in the groundwater-surface water interactions in this area.

We used natural geochemical tracers to quantify the coastal hydrodynamics, SGD flux and the associated ecological response in the Yellow River Estuary. We present here spatial distribution patterns of ^{224}Ra, ^{223}Ra and ^{226}Ra from a multi-transect field study. Water ages calculated via the “apparent radium age model” and salinity profiles of all transects are utilized to assess river plume flow rate and trajectories. We also analyzed the planktonic structure and estimated the corresponding primary production to understand the ecological response of these water flushing processes. We used a radium mass balance model to quantify the SGD flux. Finally, collected data for nutrient levels in groundwater were combined with SGD estimates to estimate nutrient budgets. An analysis of all nutrient sources and sinks was performed to better understand their dynamics in the region affected by the Yellow River. The information obtained here can be applied in the future to develop improved management strategies for protecting the environment of this area.

2. Methods

2.1. Sampling and analytical methods

Our investigations were launched in September, 2010, which is considered the wet season in this part of China. The discharge during the sampling period was 1070 m^3 s^{-1} which is more than twice the average discharge (460 m^3 s^{-1}) since 2000 (Fig. 1). The study area is confined within 37.4°–38.1°N and 119.1°–119.6°E, which covers part of the Bohai Bay and Laizhou Bay. Twenty six surface water samples were collected from six transects (C–H, Fig. 2) for radium isotopes (^{226}Ra, ^{223}Ra and ^{224}Ra), nutrients (DIN, DIP and DSi) and size-fractionated chlorophyll *a* analysis. A fresh water sample for radium analysis was collected during the same period in Lijin City, which is about 100 km upstream of the river mouth. In this investigation we report dissolved inorganic nitrogen (DIN) as the sum of NO_3^-, NO_2^-, and NH_4^+; dissolved inorganic phosphorus (DIP) as PO_4^{3-}; and dissolved inorganic silicate (DSi) as $Si(OH)_4$.

At each station, water depth, salinity, and temperature values were obtained by an XR-420 model submersible multichannel CTD (Conductivity–Temperature–Depth sensor, RBR Canada). Light penetration into the water column was measured with a 30 cm diameter Secchi disk (SD). Radium isotopes were preconcentrated by slowly passing 140-L samples through Mn-fibers that quantitatively adsorbs dissolved radium. The average adsorption efficiency of our homemade fibers was evaluated to be 98% (Xu et al., 2013). After collection, all fibers were washed thoroughly with Ra-free deionized water to remove any salt content and particulate matter and then partially dried with dry air until the water/fiber mass ratio range was around 1–2 (Sun and Torgersen, 1998; Kim et al., 2001). The short-lived radium isotopes (^{223}Ra and ^{224}Ra) were then counted via a Radium Delayed Coincidence Counting (RaDeCC) system (Giffin et al., 1963; Moore and Arnold, 1996). Long-lived ^{226}Ra was evaluated via a radon emanation line (Lucas cell) method

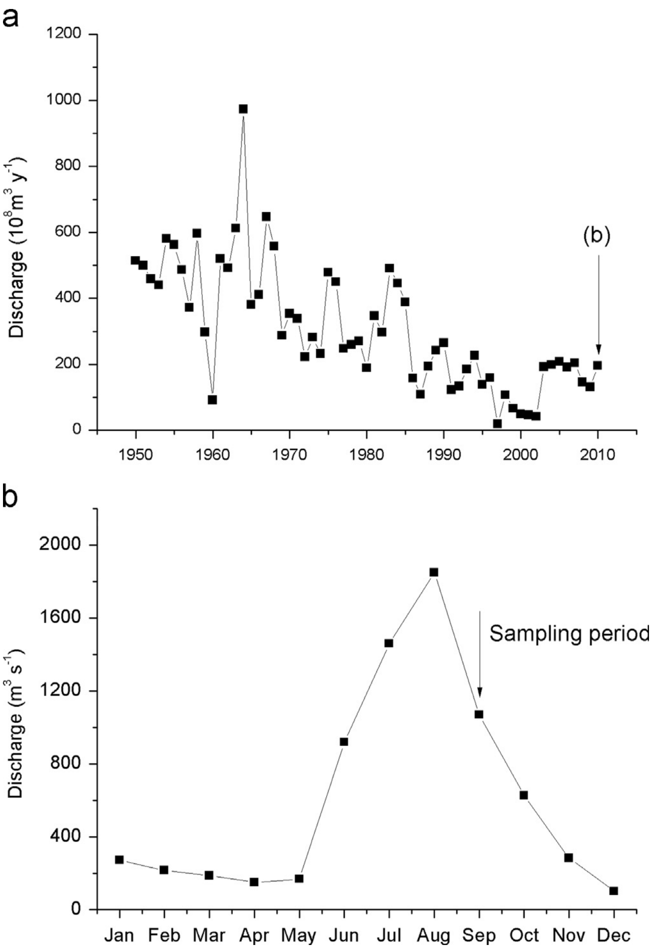

Fig. 1. Water discharge in the Yellow River, (a) annual average discharge from 1950 to 2010, (b) monthly average discharge in 2010.