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# Artificial water sediment regulation scheme influences morphology, hydrodynamics and nutrient behavior in the Yellow River estuary

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## SUMMARY

Anthropogenic controls on water and sediment may play important roles in river system transformations and morphological evolution, which could further affect coastal hydrodynamics and nutrient behavior. We used geochemical tracers to evaluate the influence of an intentional large release of water and sediment during the so-called “Water Sediment Regulation Scheme” (WSRS) on estuarine morphology, hydrodynamics and nutrients in the Yellow River estuary, China. We discovered that there was a newly formed small delta in the river mouth after the 2013 WSRS. This new morphologic feature altered terrestrial material distribution patterns from a single plume to a two-plume pattern within the estuary. Our results show that the WSRS significantly influenced the study area in the following ways: (1) Radium and nutrient concentrations were significantly elevated (two to four times), especially along the two river outlets. (2) Estuarine mixing was about two times stronger during WSRS than before. Average aerial mixing rates before and during WSRS were $50 \pm 26$ km$^2$ d$^{-1}$ and $89 \pm 51$ km$^2$ d$^{-1}$, respectively. (3) Our data is consistent with P limitation and suggest that stoichiometrically based P limitation was even more severe during WSRS. (4) All river-derived nutrients were thoroughly consumed within one to two weeks after entry to near-shore waters. (5) The extent of the area influenced by terrestrial nutrients was two to three times greater during WSRS. Human influence, such as triggered by WSRS regulations, should thus be considered when studying biogeochemical processes and nutrient budgets in situations like the Yellow River estuary.

## 1. Introduction

Most rivers deliver sediments to the ocean that are trapped on the continental shelf and significantly reshape the coastlines and sea-floor geomorphology (Meade, 1996). These sediments can affect coastal hydrodynamics, nutrient distribution patterns, and even the primary productivity of coastal ecosystems (Syvitski et al., 2005; Wang et al., 2011a). Anthropogenic activities may play an important role in river system transformations (Milliman et al., 2008; Miao et al., 2011; Zhang et al., 2015). Most world-class large rivers are heavily dammed and regulated in response to growing population demands (Dynesius and Nilsson, 1994; Rossi et al., 2009). Inter-annual river flows are often regulated between wet and dry seasons for flood control and water consumption, which also significantly impact sediment fluxes to the sea (Wang et al., 2011a; Yu et al., 2013). Case studies have been reported for a wide variety of river-delta-estuary systems, including the Nile River in Egypt, the Red River in Vietnam, the Indus River in the Himalayan region, the Pearl River and the Yangtze River in China, the Mississippi River and the Columbia River in the United States and many others (Bi et al., 2014, and references therein).

The Yellow River (Huang He) is a well-studied example of a river under heavy human control (Wang et al., 2007; Yu et al., 2013). Since the 1950s, the river has become a highly fragmented and regulated river as a result of more than 3000 reservoirs and dams constructed in the river basin (Zhang et al., 2001; Wang

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et al., 2007). The Yellow River is well known in terms of high sediment load but relatively low water discharge to the sea. The most recent data (2010–2013) shows the annual sediment load is approximately $1.5 \times 10^8$ tons, but the water discharge is only $2.2 \times 10^{10}$ $m^3$ (http://www.yellowriver.gov.cn/nishagonggao), leading to a sediment/water ratio which is about 50 times higher than the value for the Yangtze River. In order to ensure an adequate flow of water and maintain the channeling capacity of the main courses, the Yellow River Conservancy Commission (YRCC) implemented a scheme to control water and sediment discharges since 2002, the so-called "Water Sediment Regulation Scheme" (WSRS). During each annual event, a large controlled release of floodwater from reservoirs on the main stream and tributaries is used to scour the lower river reaches within a 10–20 day period (Wang et al., 2010). More details about how the WSRS is operated would be found in Kong et al. (2015a). Instantaneous flooding rates reach up to 4000 $m^3\ s^{-1}$, which is over ten-fold higher than during typical non-WSRS periods (about 300 $m^3\ s^{-1}$). Huge amounts of fresh water, sediment and associated terrestrial materials are discharged into the Yellow River estuary during this pulse delivery. Yao et al. (2009) reported that about 50% of annual nutrient fluxes were discharged into the estuary during the first WSRS conducted in 2002. Liu et al. (2012) and Liu (2015) found river nutrient transport fluxes increased 8–30 times during a WSRS period, and estuarine nutrient imbalances were aggravated. Seasonal riverine transport patterns of other terrestrial materials were also altered, e.g., uranium discharged from the Yellow River during a WSRS was about 25% of its annual flux (Sui et al., 2014). However, to what aerial and temporal extent the WSRS signal could impact the estuary and adjacent Bohai Sea remain unsolved questions.

Since unusually large amounts of sediment are delivered to the coastal region during WSRS, the estuarine morphology will also change. By using remote sensing techniques, researchers found a dramatic evolution of distributary channels in the Yellow River delta and at the river mouth (Syvitski and Saito, 2007; Wang et al., 2010; Bi et al., 2014). The mouth of the Yellow River has apparently swung northwards (2 km) and the shoreline has extended seawards (4 km) from 2002 to 2009 (Wang et al., 2010). In previous studies, we reported observations of the Yellow River plume hydrodynamics and trajectories during a non-WSRS period by using naturally occurring radium isotopes as tracers (Xu et al., 2013a). Here we address the question of whether the estuarine hydrodynamics are enhanced and become more complex during a WSRS period. We also ask if the WSRS influences the nutrient distribution and behavior within the estuary.

In the present study, we will address these questions by using robust techniques including remote sensing and geochemical isotopic tracing. We first present recent satellite images to show the latest morphological changes in the Yellow River estuary and how it impacts the materials distribution pattern. Then, we apply radium isotopes ($^{223}$Ra, $^{224}$Ra and $^{226}$Ra) as tracers to calculate estuarine water "ages" and further assess the river plume flow rate and trajectories both before and during a WSRS period. Nutrient concentrations and atomic ratios are also presented to better understand the ecological response in the Yellow River estuary and adjacent Bohai Sea under the influence of WSRS.

## 2. Methods

### 2.1. Satellite images

Remote sensing techniques have been widely applied to coastal geomorphological studies (Ryu et al., 2002; Yamano et al., 2006; Bi et al., 2014). In this study, LANDSAT images (false color images using multiple bands) were used to assess changes in morphological features of the Yellow River estuary since 2009. Satellite images of Landsat 5 Thematic Mapper (TM)/Enhanced Thematic Mapper (ETM+) and Landsat 8 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS) were downloaded from the Global Land Cover Facility Server (http://glovis.usgs.gov). There was one LANDSAT image every 16 days. The false color composite images were acquired using the software Envi 4.7, with bands of 5-4-3 for Landsat 8 and 4-3-2 for Landsat 5 as Red, Green and Blue (RGB), respectively.

### 2.2. Sampling and analytical methods

The study area is located in the Yellow River estuary, which covers part of the Bohai Sea (Fig. 1a). Seven transects and thirty five sampling stations were set up in the study area (Fig. 1b). We launched two sampling expeditions in 2014, and repeated exactly the same sampling strategy each time. The first sampling was from June 12–14, about two weeks before the WSRS. The river discharge during this sampling period ranged from 214 to 458 $m^3\ s^{-1}$. The WSRS in 2014 started on June 29 and lasted for about two weeks. Our second expedition was during this WSRS event, from July 7–9. During this period, the river discharge ranged from 2360 to 3320 $m^3\ s^{-1}$ (Fig. 1c), about one order higher than before. During both sampling periods we collected surface water samples for radium isotopes ($^{226}$Ra, $^{223}$Ra and $^{224}$Ra) and nutrients (DIN, DIP and DSi) analysis. We report here 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, salinity and temperature values were obtained by an XR-420 model submersible multichannel CTD (Conductivity–Temperature–Depth sensor, RBR Canada). Radium isotopes were pre-concentrated by slowly passing 100-l samples through manganese impregnated acrylic fibers ("Mn-fibers") that quantitatively adsorbs dissolved radium. The average adsorption efficiency of our homemade fibers was evaluated in the laboratory to be 98 ± 2% (Xia et al., 2015). After collection, all fibers were washed thoroughly with Ra-free deionized water to remove any salt content and particulate matter and then partially dried 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 (Moore and Arnold, 1996). Long-lived $^{226}$Ra was also measured by RaDeCC following the procedure described by Waska et al. (2008). The analytical precisions for all three Ra isotopes were better than 10%.

Water samples for nutrient analysis were immediately passed through 0.45 μm pore-size acetate cellulose filters. One portion of the filtrate was used for determining DIN and DIP and frozen to −20 °C until analysis. Another portion for determining DSi was stored in the dark and cold (4 °C) until analyzed (Chen et al., 2010). All nutrient concentrations were measured using a QuAAtro Continuous-Flow Analyzer (BRAN + LUEBBE, Germany) in accordance with the methods described in Grasshoff et al. (1999). The analytical precision for all nutrients was better than 3%.

### 2.3. Water ages calculated by "Apparent Radium Age" model

The "Apparent Radium Age" model was pioneered by Moore (2000) and used by multiple researchers over the past decade to evaluate water ages in continental shelf and large river plume environments (e.g., Dulaiova and Burnett, 2008; Knee et al., 2011). The water "age" represents the time passed since the short-lived radium isotopes ($^{224}$Ra and $^{223}$Ra) were added to the system from a common source with a constant isotopic composition. The age is calculated using the ratio of a shorter-lived radium