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Scaling properties of estuarine beaches

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ABSTRACT

Estuarine beaches near large rivers are dynamic systems constantly shaped by tides, waves, and fluvial sediment inputs. However, little research has been done on the intrinsic characteristics of these geomorphic systems. Using eleven high resolution bathymetries, our results show that human disturbance mingled with natural forcings have induced bathymetric changes in Nanhui beach in the Changjiang estuary, China. Isobaths display a fractal geometry, with a lower fractal dimension when tides smooth the bathymetry and a higher dimension when waves dominate. Rates of sediment accretion and erosion present a Gaussian distribution driven by tidal and wave action. Episodic extreme wave forcing or frequent land reclamation is responsible for the intermittent adjustment of the estuarine beach bathymetry. After these events the distribution of erosion and accretion becomes power-law, possibly indicating disequilibrium. The fractal dimension of isobaths and the distribution of erosion and deposition rates can therefore be used as metrics to determine the dominant processes in estuarine beaches and whether the system is close to equilibrium or not.

1. Introduction

Geomorphic systems are often nonlinear due to the presence of thresholds during their evolution (Phillips, 2006; Fagherazzi, 2008; Leonardi and Fagherazzi, 2014). Thresholds originate from the sensitivity of geomorphic systems to physical parameters, and therefore imply a high sensitivity to environmental perturbations (Pascual and Guichard, 2005). In response to external perturbations and environmental change, rates of change in a geomorphic system may present a distribution characterized by power-law, indicative of self-organization behavior (SOB) (Hallet, 1990a, b; Malamud et al., 1998; Phillips, 2003; Fonstad and Marcus, 2003).

Scaling properties are typical of systems in which a suite of local and often very different processes produce a singular global pattern (Fonstad and Marcus, 2003; Bak et al., 1987), indicting a scale invariance in the spatiotemporal dynamics of the system (Coulthard and Marco, 2010). Examples of scaling properties can be found in computer models, such as the sandpile model, the forest fire model (Malamud et al., 1998), and a model of intertidal mussel beds ecosystem (Liu et al., 2014). Evidence of scaling properties has also been found in some geomorphic phenomena, including tidal basins (Defina et al., 2007), river basins (Coulthard and Marco, 2010), riverbank systems (Fonstad and Marcus, 2003), salt marshes (Leonardi and Fagherazzi, 2014), and tidal delta (Fagherazzi, 2008). While most studies on scaling properties are based on models and observed data that present fractal characteristics, little is known about how these complex systems evolve at different spatiotemporal scales, especially to estuarine beaches.

Estuarine beaches are among the most productive ecosystems in the world, providing important habitats for wildlife. Due to combined influence of human activities and climate forcing, such as damming in the drainage basin, extraction of natural gas and oil, land reclamation in the coastal area, and sea-level rise, most estuarine beaches worldwide are facing the threats of erosional retreat (Dai et al., 2014; Syvitski et al., 2009; Anthony et al., 2014, 2015). Large scale erosion of estuarine beaches have been reported in the Asia, Europe, and Unite States (Syvitski et al., 2009; Frihy and El Banna, 1998; Yang et al., 2007).

Often the morphological characteristics of an estuarine beach (e.g. cross shore profile, isobaths curvature) remain almost un-altered while it is recessing landward (Chen, 2007). In area with large sediment supply, estuarine beach may form in front of reclaimed areas. While there is a vast literature on eroding estuarine beaches, few studies focus on the progradation of an estuarine beach (Jackson et al., 2010; Mattheus et al., 2010; Nordstrom et al., 2016). Nanhui beach, Changjiang (Yangtze) estuary, China, is a one of such cases. Nanhui beach has undergone a progressive progradation with 5 m isobath accretion

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seaward at approximately 0.5–1.2 km/yr over the past 100 years. During this progradation, the profile, slope, and curvature were maintained almost similar (Chen et al., 1985; Chen, 2007).

Despite a 70% reduction in upstream sediment load since the starting of the operation of the Three Gorges Dam (TGD) in 2003, the largest dam in the world, Nanhui beach still expands seaward maintaining the previous configuration (Dai et al., 2014; Dai et al., 2015). What processes or mechanisms have allowed these estuarine beaches to keep their original morphology even though they underwent significant environmental change at different space and time scales? Here we document the presence of scaling properties in the Nanhui beach system and further explore practical implications for the prediction of estuarine beach evolution over the world.

2. Data and methods

Nanhui beach, located at the southern part of the Changjiang estuary, China (Fig. 1), is mainly composed of well sorted sand, silty sand, and coarse silt (Fan et al., 2006; Yan et al., 2011). Nanhui beach is the largest tidal flat in the Changjiang estuary. Here, we collected published charts of the Changjiang estuary from the Navigation Guarantee Department of the Chinese Navy headquarters (NGDCNH) reporting surveys conducted in 1958, 1978, 1997, 2000, 2002, and 2004 (Table S1). The charts were integrated with bathymetrical surveys recorded in the Nanhui beach by the Shanghai Institute of Geological Survey from 2009 to 2013 (Table S1). The daily wave heights during 2008 at Nancaodong, the nearshore station of Nanhui beach, were obtained from Shanghai Estuarine and Coastal Science Research Center (www.ecsrc.org) (Fig. S1). Episodic storms passing over this region producing large storm surges were collected at Wusong from the Hydrological Bureau of the Changjiang estuary since 1955 (Table S2). The yearly sediment discharge at Datong, the tidal limit of the Changjiang estuary, was acquired from the Bulletin of China River Sediment during the period 1953–2013 (www.cjh.com.cn).

All bathymetrical surveys were conducted by DESO-17 echo-sounder in early May or June, prior to peak discharge and typhoon seasons, and completed before August (Dai et al., 2014). The spatial resolution for all charts is 0.05–1 km with vertical error of approximately 0.1 m. Based on the digitizing procedure of Blott et al. (2006), the bathymetry reported in the charts were digitized and analyzed by using ArcGis9.3 software. All digitized data were transferred from their original projections into Beijing 54 coordinates in ArcGis 9.3 to form a standardized digital terrain model (DTM) for each digitized chart. Subsequently, different bathymetric contours (e.g. 0 m, −1 m, and −2 m) and elevation variations along four transverse sections of each year were extracted from the DTMs, respectively (Fig. 1). The fractal dimension (*D*) of the contour lines in different years were measured through box counting method (Feder, 1988). While the contour lines in given years are covered by non-overlapping D-dimensional hyper-spheres of Euclidean radius, *r*, and the number, *N*(*r*), of the spheres is counted. Therefore, for a fractal system the 'box-counting method' was proposed to calculate *D* as follows (Sahimi, 2000):

$$N(r) \sim r^{-D} \tag{1}$$

where the unit length of *r* is 100 m. To illustrate bathymetric variations of Nanhui beach in different years, we compute the distribution of bottom variations $\Delta h(p, t_1, t_2)$ in Nanhui beach, described by the following equation:

$$\Delta h(p, t_1, t_2) = h_2(p, t_2) - h_1(p, t_1), \tag{2}$$

where $h_1(p,t_1)$ and $h_2(p,t_2)$ are water depth in time t_1 and t_2 at any position $p(x,y)$, respectively. Variations in $\Delta h(p,t_1,t_2)$ reflects erosion and deposition in Nanhui beach.

A Gaussian distribution, already been adopted in geoscience research (Montreuil et al., 2014; Ge et al., 2017), is used in this study to simulate the frequency distribution of $\Delta h(p,t_1,t_2)$ throughout the entire study area:

$$f(\Delta h) = a \exp^{(-(\Delta h - b)^2/2c^2)}, \tag{3}$$

Where $f(\Delta h)$ is the probability density function of Δh, with *a* indicating the height of the curve's peak, *b* indicating the position of the center of the peak, and *c* indicating the standard deviation. When the Gaussian distribution fails to approximate the bathymetric variations, a power-law distribution is adopted. Thereafter, we calculate frequency distribution for bathymetric changes of different years. In addition, the changes of daily wave height were also explored in 2008.

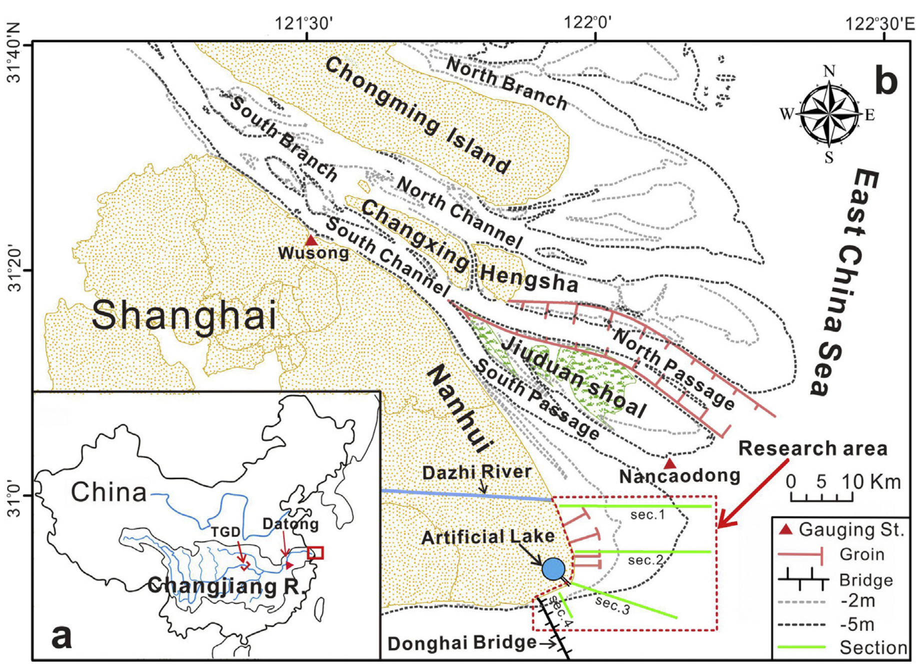

Fig. 1. Research area and the present Changjiang estuarine topography in 2013 (Groin in this Figure was used to flat reclamation).