Marine Geology 404 (2018) 130–136

Contents lists available at ScienceDirect

Marine Geology

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

Scaling properties of estuarine beaches

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ARTICLE INFO

Editor: E. Anthony

Keywords:
Estuarine beach
Distribution of rates of erosion and deposition
Morphodynamic process
Fractal dimension of isobaths
Changjiang

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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https://doi.org/10.1016/j.margeo.2018.07.011
Received 13 September 2017; Received in revised form 7 July 2018; Accepted 23 July 2018
Available online 25 July 2018
0025-3227/

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):

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

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:

$$\Delta h(p,t_1,t_2) = h_2(p,t_2) - h_1(p,t_1), \quad (2)$$

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:

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

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.

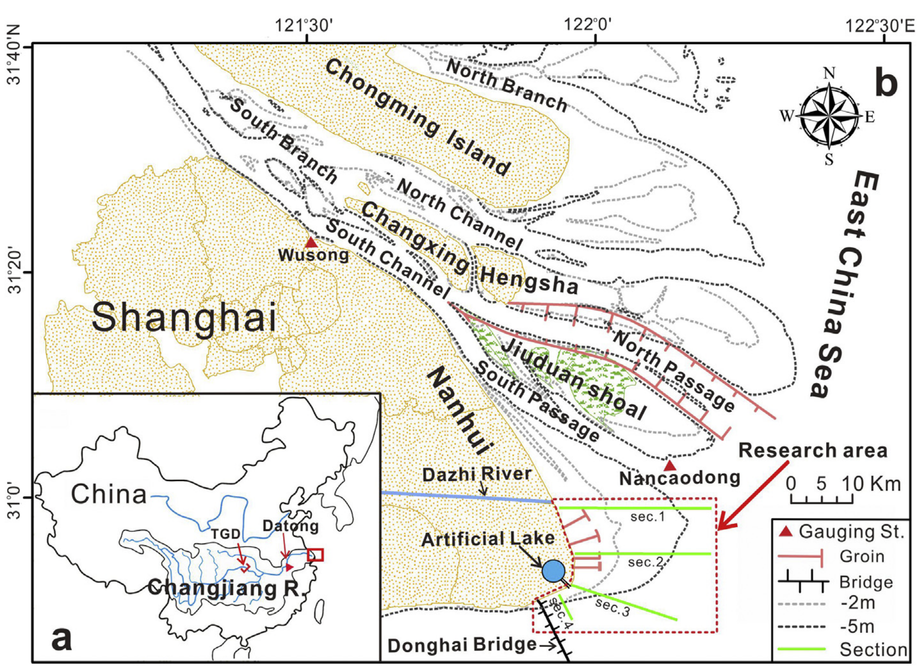

Fig. 1. Research area and the present Changjiang estuarine topography in 2013 (Groin in this Figure was used to flat reclamation).

3. Results

3.1. Invariant power-law scaling

It can be found that all bathymetries in Nanhui beach from 1958 to 2013 exhibit similar fan form (Fig. 2a–k), even though the water depth at any position could have experienced complex environmental change during this period. The bathymetric contours of each year show an echelon shape, such as shown for 2013 (Fig. 2l, Fig. S1). Further, after dividing the bathymetry in squares of size *r*, there is a good correlation between the number of squares $N(r)$ containing a contour line and the corresponding scale *r* at a significant level of 0.001 (Fig. 3a–k, Table S3). This means that bathymetric contours of Nanhui beach in different years have an inverse power-law magnitude-frequency relation, which is in agreement with those of classic self-similar fractals of geomorphic systems, such as coastlines, tidal delta, and lakes (Fagherazzi, 2008; Turcotte, 2007; Mandelbrot, 1967). Moreover, there is a statistically significant difference between the fractal dimension in the period 1958–2004 (average value of 1.553) and the fractal dimension in the period 2009–2013 (average value of 1.596) (two-sample *t*-test with $p < 0.05$) (Fig. 3l). Fractal values also show a statistically significant upward trend during 1958–2013 ($p < 0.01$, Fig. 3l).

3.2. Erosion and accretion patterns

The frequency distribution of water depth at different locations in the study area exhibits certain characteristics: a gradual increase in the frequency of water depths above 0 m and below −6 m and a frequency trough approximately between −2 and −3 m, except in 1997 (Fig. S2). The frequency curves of water depths become bimodal between 2009 and 2013, with two peaks around −1 to −2 m and −3 to −4 m, respectively (Fig. S2g–k).

Changes in Nanhui beach bathymetry Δh in given time intervals are shown in Fig. 4. Between 1958 and 1978, the entire area experienced an average accretion between 1 and 2 m, with local intensive accretion over 2 m in the southwestern part. Patched erosion through the whole area can also be observed (Fig. 4a). Similar phenomena of a mosaic pattern of erosion and accretion can be found in bathymetric changes (Fig. 4b–e). We also notice a relatively large and localized erosion and accretion area in the southwestern part (Fig. 4b–f).

Bathymetric variations occurred in a short time (every year), indicating an overall large-scale accretion (Fig. 4g–i). Another large-scale erosion with patched accretion can be found in Fig. 4j. Moreover, the mean yearly accretion rate in different years is almost always below 0.2 m/yr (Fig. 4a–e, g–j, Fig. S3), while erosion rates during 2004–2009 are approximately 0.2 m/yr (Fig. 4f, Fig. S3).

3.3. Simulation of the distribution of bathymetrical changes

The distribution of erosion/deposition, Δh is well approximated by a Gaussian probability density function from 1958 to 2009 (time intervals 1958–1978, 1978–1997, 1997–2000, 2000–2002, 2002–2004, and 2004–2009) with correlation coefficients over 0.95 (Fig. 5a–b, Fig. S4, Table S3). The mean value in this period is mainly around zero (Fig. 5a–b, Fig. S4). Values of Δh between −0.3 m and 0.3 m occur in about 75% of the studied area (Fig. 5a–b, Fig. S4).

In the time periods after 2009 (2009–2010, 2010–2011, 2011–2012, and 2012–2013) a Gaussian model does not fit the distribution of erosion/deposition. In these periods, a power-law distribution is adopted to approximate the statistical characteristics of erosion/deposition events. It can be shown that both erosion and accretion events are well simulated by a power-law distribution, with a significant level of 0.001 (Fig. 5c–d, Fig. S5). Meanwhile, for the entire period 1958–2013, the studied areas with Δh above 1 m or below −1 m contribute less than about 10% of the total area in Nanhui beach (Fig. 5a–d, Fig. S4–5).

4. Discussion

It has been indicated that many geomorphic systems, such as coastlines, topography contours and lakes, display classic self-similar fractals with power-law scaling (Fonstad and Marcus, 2003; Turcotte, 2007). Since the bathymetric data of all Nanhui charts were surveyed in early May or June under calm weathers, sediment that were transported into the Nanhui beach could have had enough time for self-adjust and reach equilibrium before new storms with relatively large waves hit the Changjiang estuary (Fig. S6, Table S2). In subsequent months, local sediment transport into this area usually exceeds sediment output, and the sediment bottom can be subject to large-scale alterations disrupting the morphological equilibrium of Nanhui beach.

In the long term, Nanhui beach is prograding with the −5 m isobath moving seaward (Fig. S7), which means the distal decrease in sediment load triggered by the Three Gorges Dam is unrelated to the present Nanhui topographical variations. A large-scale erosion event occurred between 2004 and 2009 (Fig. 4f) due to the successive storms in 2007 (Vipa in 9.19, Krosa in 10.7, Table S2), indicating that the original equilibrium state was disrupted, and the system started shifting to a

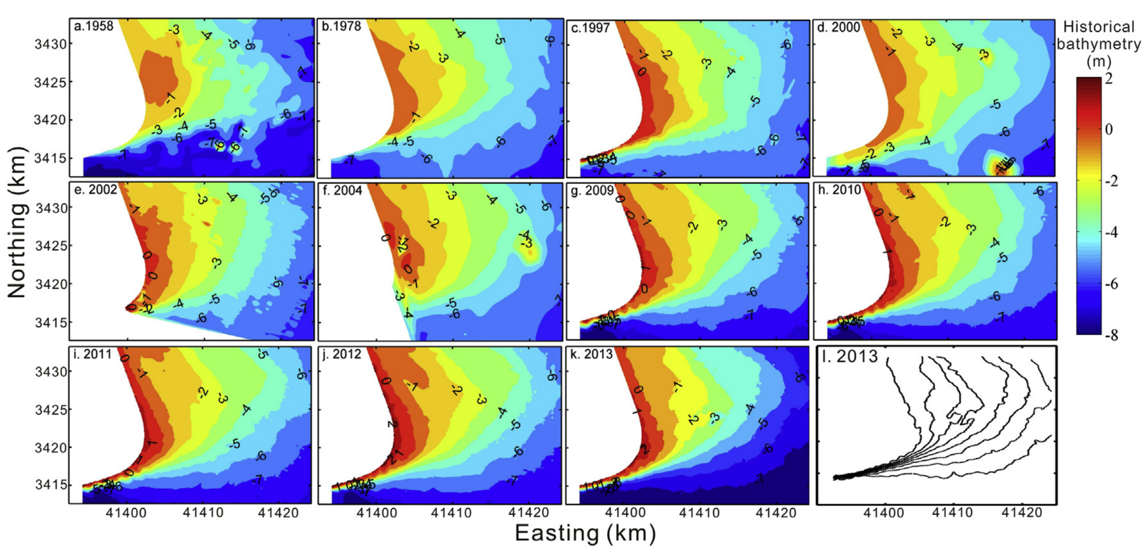

Fig. 2. Distribution of the Nanhui beach bathymetry in different years (a–k is bathymetric distribution in given year, and l is a contours drawn of bathymetric image in 2013).

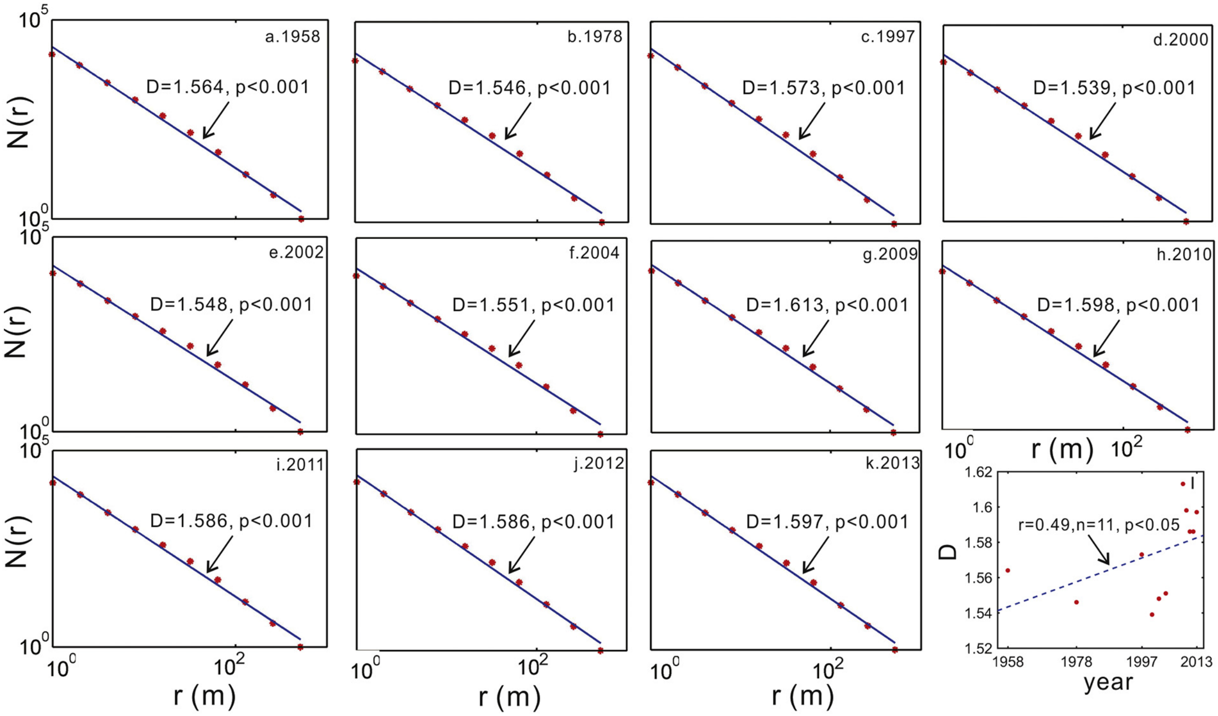

Fig. 3. Scale invariance of the topographic contours in different years.

new state. This is also confirmed by the spatial location of the −5 m isobath, which regressed seaward from 2004 to 2009 (Fig. S7). Yet this shift did not produce large erosion rates or deposition rates. Hence, large-scale adjustments in Nanhui beach occur with locally mild fluctuation in elevation.

The morphology of Nanhui beach is impacted by tidal currents and waves. Some cross-shore elevation profiles along Nanhui beach are convex (a sign of tidal dominance) while some are concave (a sign of wave dominance, Fig. 6). The inner parts of Nanhui beach, closer to the Changjiang River (e.g. Sec.1 in Fig. 1 and Fig. 6) displays a constant convex profile with tidal ridges. The cross-shore profile becomes progressively more concave from the inner to the outer parts of the beach (e.g. from Sec. 1 to Sec. 4 in Fig. 6), as well as in time. The convex shape of the inner part is thus dominated by cross-shore tidal currents with less waves influence (Pritchard et al., 2002), while waves become more important in the outer part (Pritchard et al., 2002; Friedrichs, 2011).

Nanhui beach was also subject to several large-scale reclamation projects since 2000, with the construction of cross-shore groins and along-shore dykes aiming at trapping sediment (Fig. S9) (Dai et al., 2015). Elevation variations along section 2 of the reclaimed area show an almost linear accretion in areas with water depth below 2 m after 2004. Water depths above 2 m experienced little impact, displaying an undulated topography as a result of the mutual action of tides and waves (Fig. 6).

Temporal variations of fractal values for different bathymetries of Nanhui beach reflect external interferences. The bathymetry of Nanhui beach in 1958 represents its natural state with out of order topographical distribution (Fig. 2a, Fig. S1a) (Chen et al., 1985) due to the impacts from the largest flood of 1954 in the historical record (Mei et al., 2018), this bathymetry display a relatively large fractal value. Between 1958 and 1997, Nanhui beach underwent a slow adjustment with almost unchanged topography due to the long-term effect of waves and tides, leading to a reduction of box-counting fractal dimension (Table S3). The typhoon of 1997, the largest in the past 50 years in Shanghai, induced large-scale erosion in Nanhui beach, with rapid readjustment of the bathymetry characterized by a high fractal value of

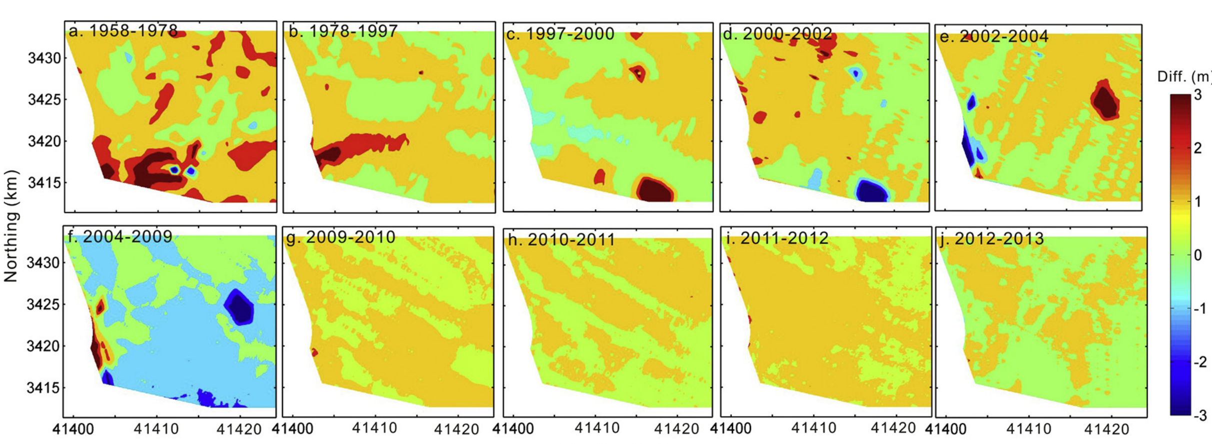

Fig. 4. Changes of accretion and erosion (depth of later time minus that of the previous time) in the Nanhui beach in different years.

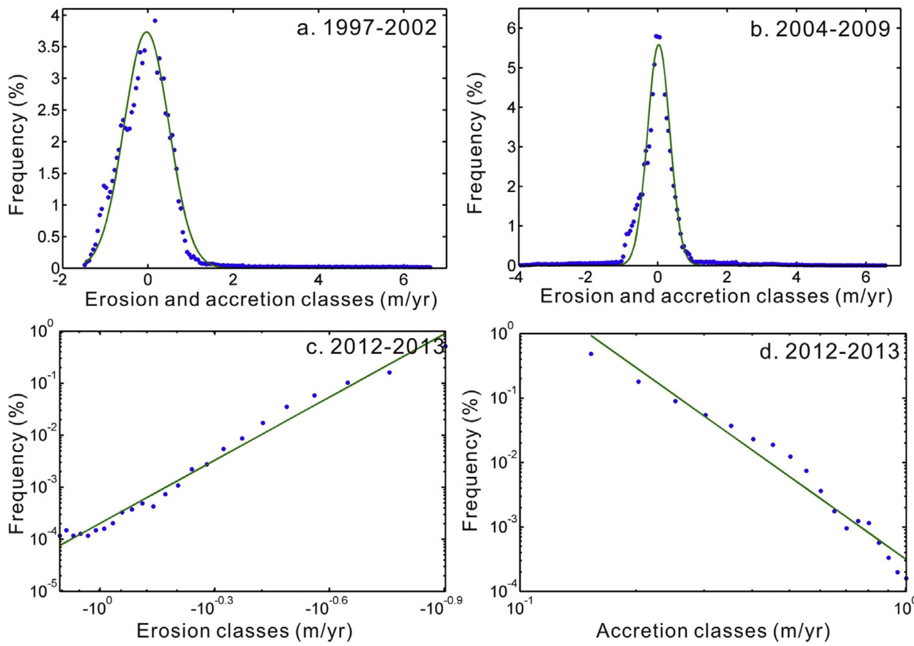

Fig. 5. Frequency of occurrence of erosion and accretion events in different intervals in different years.

1.573 (Fig. 3l). Low fractal values of Nanhui beach between 2000 and 2004 show that the tidal flat system has experienced bottom adjustment after the 1997 typhoon, with a smoothing of the isobaths (Table S2). Due to frequent tidal flats reclamations with groins construction in 2003, 2007, and 2009, the tidal fluxes in and out the south passage cannot reach the shallow part of area. With weaker tidal fluxes, wave action has likely become the dominant geomorphic agent. Contrary to tides, waves smooth less the contour lines, producing local erosion and deposition with a higher fractal dimension. Thereof, human disturbance mingled with natural forcings, likely producing a complex morphology with a bimodal distribution of elevations (Fig. S2) and fractal values above 1.58. Significant differences are observed between the fractal values of 1958–2004 and 2009–2013 (two-sample *t*-test with $p < 0.05$ (Fig. 3l). Therefore, the controlling factor of Nanhui topographic shifts from natural forcing to land reclamation and natural forcing, which respectively dominate the bathymetry below and above 2 m water depth. Accordingly, the fractal value that indicates the morphology complexity shows an increasing trend (Fig. 3l). This result can be used for the characterization and management of estuarine beaches: by computing the fractal dimension you could determine whether tidal fluxes or waves are the dominant process in the area.

Further, the influence of land reclamation is relatively small before 2004, when Nanhui's bathymetric changes were dominated by low-energy natural processes (tidal current, wave). These conditions were characterized by topographic variations between −0.3 m and 0.3 m (Fig. 5a–b, Fig. S4). Episodic storm events (Table S2) that caused strong erosion and deposition over ± 0.3 m account for approximately 25% of the area. Under the influence of low-energy and occasional high-energy events, bottom elevation changes of Nanhui exhibited weak variations and followed a Gaussian distribution before 2004. Land reclamation since 2009 has triggered a strong deposition within the area below the 2 m water depth (Figs. 6, S9), while the area above 2 m displays no obvious change in morphology. As a consequence, bottom elevation changes of Nanhui shifted to a power-law distribution due to the interference of human activities. From a management point of view, a manager could measure the distribution of bottom change in one year, if it is Gaussian then little change is expected, if it is exponential then much more change will occur in the following years.

In addition, many studies have linked changes in estuarine beaches to variations in distal sediment fluxes from upstream (Syvitski et al., 2009; Yang et al., 2007; Darby et al., 2006; Fan et al., 2006). However, Nanhui beach shows scale invariance during the past 60 years while keeping the fan shape due to large-scale random sediment diffusion and remobilization. Further, our data indicate that Nanhui beach is accreting seaward with elevation changes following a Gaussian or power-law distribution, despite large fluctuations in elevation between 1953 and 2013 when sediment from upstream decreased drastically by 70% (Dai et al., 2014), frequent land reclamation occurred since the 1980s, and episodic extreme storm events took place in the last 50 years (Dai et al., 2014; Chen, 2007). The relatively stable frequency distribution of bathymetric changes over Nanhui beach indicates that the beach has self-restoring capacity against dramatic environmental variations. In light of the present sediment decrease in many large rivers of the world with risk of estuarine beach loss, scale invariance should be recognized as inherent dynamics behind changes in estuarine beach. Our results are important to mediate, mitigate, and adapt impacts from the combined effects of global (e.g., sea-level rise) and local (e.g., reclamation) drivers.

Frequent low-energy wave events produce a low fractal dimension of isobaths in Nanhui beach, while episodic large-wave disturbances can be responsible for an increase in fractal dimension. Our results indicate that inherent self-adjustment of large-scale sediment diffusion and deposition during low-energy periods allow Nanhui beach to reach an equilibrium after large wave disturbance. This property is in coincidence with variations of low wave heights that accounts for about 90% PDF in 2008 (Fig. S9). It is suggested that morphological metrics like the fractal dimension of isobaths and the distribution of erosion/deposition rates can predict for the long-term evolution of estuarine beaches.

Moreover, our results indicate that inherent bathymetric self-adjustment during low-waves conditions drives the system to a new equilibrium after a high-energy wave event. Phase transition with spatial shift seaward can be produced after large wave energy disturbance in Nanhui beach. This has important consequences for estuarine beach management. The best time for reclamation is after a seaward shift, which is the beginning of estuarine beach recovery. In view of the serious challenges faced by estuarine beaches, we argue that scaling properties of the estuarine beach morphology should be considered within the framework of environmental decision making.

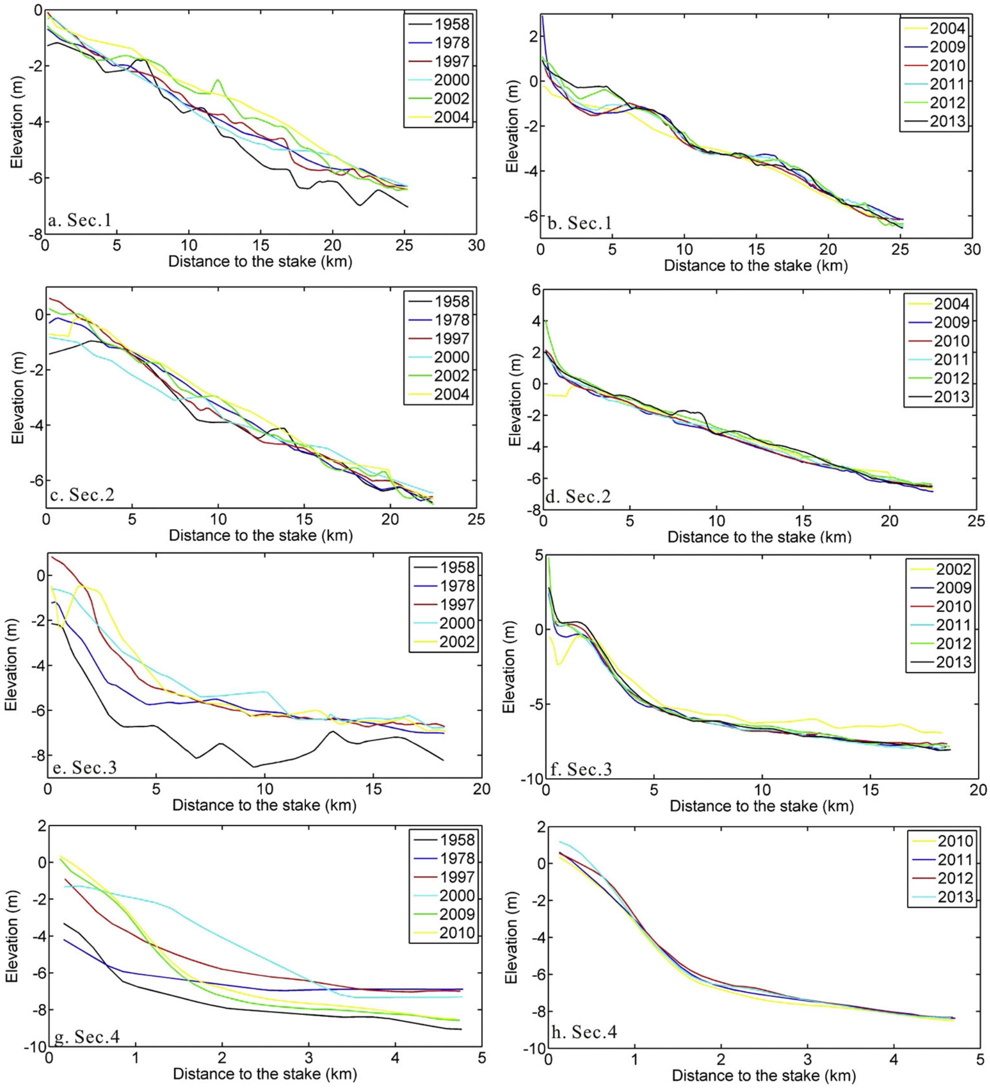

Fig. 6. Beach profile changes of the different parts along Nanhui (the distance to 1958 0 m shoreline stake).

5. Conclusion

How geomorphic systems undergo external environmental changes at different scales is often linked to geomorphological processes and associated controlled forcings. Scaling behavior exists throughout these systems and it can be well explained by nonlinear dynamic processes. Here, using a typical example of estuarine beach in Nanhui beach, Changjiang estuary, China, we show that this geomorphic system exhibits fractal properties with power-law scaling. Nanhui morphology tends to become more complex with a larger fractal dimension when anthropogenic processes overcome natural ones. Low-energy natural forcings cause large-scale sediment diffusion that promotes the return of the beach to its original state. Extreme typhoon events result in large sediment mobilization and disruption of the morphological equilibrium of Nanhui beach. Human disturbance mingled with extreme natural forcings result in a power-law distribution of bathymetric changes, while sediment accretion and erosion present a Gaussian distribution during low-energy periods. We argue that scaling properties of estuarine beaches can provide vital information to guide restoration and mitigate impacts from the combined effects of natural forcings and anthropogenic interferences.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.margeo.2018.07.011.

Acknowledgements

This study was supported by the National Key Research and Development Program of China (2017YFC0506002) , and National Science Foundation of China (NSFC) (41576087, 41706093). Data in this study can be requested from Z.J. Dai. We are also very grateful to two anonymous reviewers and Professor Edward Anthony for their constructive suggestions that helped to improve the previous manuscript.

References

Anthony, E.J., Marriner, N., Morhange, C., 2014. Human influence and the changing geomorphology of Mediterranean deltas and coasts over the last 6000 years: from progradation to destruction phase? Earth Sci. Rev. 139, 336–361.

Anthony, E.J., Brunier, G., Besset, M., Goichot, M., Dussouillez, P., Nguyen, V.L., 2015. Linking rapid erosion of the Mekong River delta to human activities. Sci. Rep. 5, 14745.

Bak, P., Tang, C., Wiesenfeld, K., 1987. Self-organized criticality: an explanation of the 1/f noise. Phys. Rev. Lett. 59, 381.

Blott, S.J., Pye, K., Van Der Wal, D., Neal, A., 2006. Long-term morphological change and its causes in the Mersey Estuary, NW England. Geomorphology 81, 185–206.

Chen, J.Y., 2007. Research and Practice of Estuary and Coast in China. Higher Education Press, Beijing, China.

Chen, J., Zhu, H., Dong, Y., Sun, J., 1985. Development of the Changjiang estuary and its submerged delta. Cont. Shelf Res. 4, 47–56.

Coulthard, T., Marco, V.D.W., 2010. Self-organized criticality in river basins: challenging

sedimentary records of environmental change. Geology 38 (1), 87–90. https://doi.org/10.1130/G30490.1.
Dai, Z., Liu, J.T., Wei, W., Chen, J., 2014. Detection of the Three Gorges Dam influence on the Changjiang (Yangtze River) submerged delta. Sci. Rep. 4, 6600. https://doi.org/10.1038/srep06600.
Dai, Z., Liu, J.T., Wen, W., 2015. Morphological evolution of the South Passage in the Changjiang (Yangtze River) estuary, China. Quat. Int. 380–381, 314–326.
Darby, S.E., Hackeny, C., Leyland, J., Kummu, M., Lauri, H., Parsons, D.R., Best, J., Nicholas, A.P., Aalto, R., 2006. Fluvial sediment supply to a mega-delta reduced by shifting tropical-cyclone activity. Nature 539, 276–279. https://doi.org/10.1038/nature19809.
Defina, A., Carniello, L., Fagherazzi, S., D'Alpaos, L., 2007. Self-organization of shallow basins in tidal flats and salt marshes. J. Geophys. Res. 112, 15–36. https://doi.org/10.1029/2006JF000550.
Fagherazzi, S., 2008. Self-organization of tidal deltas. Proc. Natl. Acad. Sci. U. S. A. 105, 18692–18695. https://doi.org/10.1073/pnas.0806668105.
Fan, D., Guo, Y., Wang, P., Shi, J.Z., 2006. Cross-shore variations in morphodynamic processes of an open-coast mudflat in the Changjiang Delta, China: with an emphasis on storm impacts. Cont. Shelf Res. 26, 517–538.
Feder, J., 1988. Fractals. Plenum Press, New York, pp. 283.
Fonstad, M., Marcus, W.A., 2003. Self-organized criticality in riverbank systems. Ann. Assoc. Am. Geogr. 93, 281–296.
Friedrichs, C.T., 2011. Tidal flat morphodynamics: a synthesis. In: Treatise on Estuarine and Coastal Science: Sedimentology and Geology, pp. 137–170. https://doi.org/10.1016/B978-0-12-374711-2.00307-7.
Frihy, O.E., El Banna, M.M., 1998. Natural and human impact on the northeastern Nile Delta coast of Egypt. J. Coast. Res. 14, 1109–1118.
Ge, Z., Dai, Z., Pang, W., Li, S., Wei, W., Mei, X., Huang, H., Gu, J., 2017. LIDAR-based detection of the post-typhoon recovery of a meso-macro-tidal beach in the Beibu Gulf. China. Mar. Geol. 391, 127–143.
Hallet, B., 1990a. Spatial self-organization in geomorphology: from periodic bedforms and patterned ground to scale-invariant topography. Earth Sci. Rev. 29 (1–4), 57–75. https://doi.org/10.1016/0012-8252(0)90028-T.
Hallet, B., 1990b. Spatial self-organization in geomorphology: from periodic bedforms and patterned ground to scale-invariant topography. Earth Sci. Rev. 29, 57–75.
Jackson, N.L., Nordstrom, K.F., Saini, S., Smith, D.R., 2010. Effects of nourishment on the form and function of an estuarine beach. Ecol. Eng. 36 (12), 1709–1718.
Leonardi, N., Fagherazzi, S., 2014. How waves shape salt marshes. Geology 42, 887–890.
Liu, Q.X., Herman, P.M.J., Mooij, W.M., Huisman, J., Scheffer, M., Han, O., Van De Koppel, J., 2014. Pattern formation at multiple spatial scales drives the resilience of mussel bed ecosystems. Nat. Commun. 5, 5234.
Malamud, B.D., Morein, G., Turcotte, D.L., 1998. Forest fires: an example of self-organized critical behavior. Science 281, 1840.
Mandelbrot, B., 1967. How long is the coast of Britain? Statistical self-similarity and fractional dimension. Science 156, 636–638.
Mattheus, C.R., Rodriguez, A.B., McKee, B.A., Currin, C.A., 2010. Impact of land-use change and hard structures on the evolution of fringing marsh shorelines. Estuar. Coast. Shelf Sci. 88 (3), 365–376.
Mei, X.F., Dai, Z.J., Darby, S.E., Gao, S., Wang, J., Jiang, W.G., 2018. Modulation of extreme flood levels by impoundment significantly offset by floodplain loss downstream of the Three Gorges Dam. Geophys. Res. Lett. 45, 3147–3155.
Montreuil, A., Levoy, F., Bretel, P., Anthony, E.J., 2014. Morphological diversity and complex sediment recirculation on the ebb delta of a macrotidal inlet (Normandy, France): a multiple LiDAR dataset approach. Geomorphology 219, 114–125.
Nordstrom, K.F., Jackson, N.L., Farrell, E.J., Rafferty, P., Tengwall, C., 2016. Restoring sediment to compensate for human-induced erosion of an estuarine shore. Geomorphology 262 (1), 37–46.
Pascual, M., Guichard, F., 2005. Criticality and disturbance in spatial ecological systems. Trends Ecol. Evol. 20, 88.
Phillips, J.D., 2003. Sources of nonlinearity and complexity in geomorphic systems. Prog. Phys. Geogr. 27 (1), 1–23. https://doi.org/10.1191/0309133303pp340ra.
Phillips, J.D., 2006. Evolutionary geomorphology: thresholds and nonlinearity in landform response to environmental change. Hydrol. Earth Syst. Sci. 10 (5), 731–742. https://doi.org/10.5194/hess-10-731-2006.
Pritchard, D., Hogg, A.J., Roberts, W., 2002. Morphological modelling of intertidal mudflats: the role of cross-shore tidal currents. Cont. Shelf Res. 22, 1887–1895. https://doi.org/10.1016/S0278-4343(02)00044-4.
Sahimi, M., 2000. Fractal-wavelet neural-network approach to characterization and upscaling of fractured reservoirs. Comput. Geosci. 26, 877–905.
Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., 2009. Sinking deltas due to human activities. Nat. Geosci. 2, 681–686.
Turcotte, D.L., 2007. Self-organized complexity in geomorphology: observations and models. Geomorphology 91, 302–310.
Yan, H., Dai, Z., Li, J., Zhao, J., Zhang, X., Zhao, J., 2011. Distributions of sediments of the tidal flats in response to dynamic actions, Yangtze (Changjiang) Estuary. J. Geogr. Sci. 21, 719–732.
Yang, S.L., Zhang, J., Xu, X.J., 2007. Influence of the Three Gorges Dam on downstream delivery of sediment and its environmental implications, Yangtze River. Geophys. Res. Lett. 34.