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Morphodynamics at the Coastal Zone in the Laizhou Bay, Bohai Sea

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ABSTRACT

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Morphogenetic processes of the Yellow River Delta and the Laizhou Bay, Bohai Sea, China, have to be described by the interrelation of riverine sediment supply, relative sea level change and the effects of wind driven waves and nearshore currents. The research area is regarded a natural laboratory of the development of river dominated coastal zone with interfering natural and anthropogenic forcing factors. As well for the historical hindcast as for future projections of the morphogenetic coastal processes the Dynamic Equilibrium Shore Model (DESM) can be applied. This model generalizes the standard Bruun rule model and generates Digital Elevation Models (DEMs) scenarios on decadal to centennial time scales for the geological past and future. The basic concept is a dynamic equilibrium coastal profile evolution in adaption to the sediment budget in a spatially three-dimensional domain. By adding parameters to account for sediment mass contribution from riverine sediment flux, the DESM can be used to explore coastal morphological equilibrium states responding to sediment budget changes for river-dominated coastal zones. For the parameterization historical maps of the southern Bohai Sea have been applied to reconstruct paleo-coastlines for the 19th century for the comparison with a modern DEM. Gauge measurements provided the data for an estimation of trends in sea level change for the Laizhou Bay on the decadal scale. Modern sea level rise together with reduced riverine sediment supply caused by anthropogenic activities such as damming up-streams may change the depositional environment at the Yellow River Delta and related areas of the Laizhou Bay from river dominated (progradational) to wave dominated (regressive) environment.

ADDITIONAL INDEX WORDS: *Coastal morphodynamics, Laizhou Bay, Dynamic Equilibrium Shore Model; river sediment flux; relative sea level change.*

INTRODUCTION

Coastal morphodynamic evolutions are subject to changing climate such as accelerated rising sea level and increasing frequency of storm events (IPCC, 2013). Furthermore, coasts are more vulnerable at the glacial-isostatiscal subsiding coastal areas than the uplifting coasts (Harff *et al.*, 2007). During the last century, most deltas in the world are also vulnerable to subsidence because of decreasing riverine sediment sources or/and sediment compaction that are largely influenced by anthropogenic activities (Saito *et al.*, 2007; Syvitski *et al.*, 2009; Syvitski and Kettner, 2011). Special attentions should be given to these subsiding deltas when considering impacts of rising sea level on the coasts (Nicholls and Cazenave, 2010).

River mouth systems in the Bohai Sea (Yellow River mouth) are in the focus of environmental research because of the enormous economic importance of the area so that for sustainable planning and management functional models of the environmental system are needed. These models allow the generation of scenarios not only for recent processes, but also for the geological development of the area and its future projection. The comparison of coastal and river mouth environments of different marginal seas will lead to a deeper understanding of the processes within the land-ocean transition zones. In the past, comparative research studies have been already conducted along the northern shelf of the South China Sea, in particular in the Pearl River Estuary and the Beibu Gulf (Harff *et al.*, 2010; 2013; Yao, 2009). In both cases the studies benefit from two preceding research projects run along the southern coast of the Baltic Sea: "Dynamics of Natural and Anthropogenic Sedimentation-DYNAS" (Harff *et al.*, 2009) and "Sinking Coasts-Geosphere, Ecosphere and Anthroposphere of the Holocene Southern Baltic Sea-SINCOS" (Harff and Lüth, 2011). Because of its steep gradients of oceanographic and geological parameters, such as salinity, sea level change, and vertical displacement of the Earth's crust (Glacio-Isostatic Adjustment-GIA), the Baltic Sea serves as a model ocean where coastal

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and shelf sea processes can be studied exemplarily in an exceptional manner. So, special function-models have been developed within the frame of the SINCOS and DYNAS projects allowing as well the historical hindcast as future projection of the development of coastal areas as a result of interference of geological, climatic, oceanographic driving forces with anthropogenic activities (Harff and Lüth, 2011; Harff and Meyer, 2011; Zhang *et al*., 2012). Within the frame of a research project "Coastal Changes at the Southern Baltic Sea-Past and Future Projection- CoPaF" the SINCOS approach has been specified in particular to morphodynamic changes of the coastal zone affected by the climatically controlled sea level rise (Deng *et al*., 2014). The level of conceptual generalization was set for any case to let scientists apply the corresponding models not only to the Baltic Sea, but also to other marginal seas even in different climatic zones and different oceanographic conditions.

Parameterization of a long-term multi-scale morphodynamic model to generate future scenarios has to base on the information derived from the reconstruction of paleo-coastal geomorphological changes with similar duration to the future scenarios (*e.g.* Deng *et al*., 2014; Dissanayake *et al*., 2012; Zhang *et al*., 2011). This fact highlights the importance of modelling paleo-coastal geomorphology at the corresponding time span to future projection (i. e. ca. 100 years according to common climate modelling periods). A model to generate paleo-digital elevation scenarios has been elaborated for the wave-dominated sandy coast (i. e. the Pomeranian Bay, southern Baltic Sea) by Deng *et al.* (2014). This so-called Dynamic Equilibrium Shore Model (DESM) generates paleo-Digital Elevation Models (DEMs) on decadal to centennial time scales. The basic concept is a dynamic equilibrium coastal profile evolution in adaption to the sediment budget in a spatially three-dimensional domain. This concept is generalised from the standard Bruun rule model (Bruun, 1962; 1988). Our main objective is to generalize the DESM by adding parameters to account for sediment mass contribution from riverine sediment flux, and to use the model to explore coastal morphological equilibrium states responding to sediment budget changes.

At the Laizhou Bay, located at the south of Bohai Sea, fluviatile sources supply most of the sediments accumulated at sinks along the coast. Among numerous rivers merging the southern Bohai Sea, the Yellow River dominates fluviatile sediment sources. The main sediment sink area coincides with the subsiding zone of the western Laizhou Bay, whereas the eastern Laizhou Bay coast belongs to the uplifting Shangdong Peninsula (Li *et al*., 1991). It is notable that besides natural forces, during the last decades anthropogenic factors influence increasingly coastal morphogenesis. Dams and reservoirs erected upstream diminish continuously the suspended matter load of Yellow River delivered to the receiving marine basins (Wang *et al*., 2007). This decrease makes sea level change and wind-wave dynamics become increasingly important for the coastal development compared to fluviatile factors. At the same time the tide plays the dominant role in transporting sediments out of the sheltered embayment system to deeper shelf and the Yellow Sea (Bian *et al*., 2013; Lu *et al*., 2013). Numerical studies confirm the interpretation and estimation of Yang and Liu (2007) that along shelf sediment transport delivered by Yellow River formed clinoform deposits along the eastern tip of Shandong Peninsula in the Yellow Sea during the last 7000 years. These studies providing qualitative and quantitative information of sediment source to sink transport make the Laizhou Bay and the adjacent Yellow River Delta as an ideal case for generalising the DESM model by applying sediment mass balancing.

ENVIRONMENTAL SETTING

The Bohai Sea (Figure 1), a marginal inland sea of China, serves as a key area to study the interrelation of different factors influencing the relative sea level and coastline change. As a semi-enclosed marginal Sea the shallow Bohai Sea (average depth of 18 m) is separated in the Southeast from the Yellow Sea by the Shandong Peninsula. Through the 90 km wide Bohai Strait the Bohai Sea is connected with the Yellow Sea. Tidal dynamics and wind waves are main processes ruling morphodynamics.

The general development of the Bohai Sea is determined by the postglacial Sea level rise. Regionally, the general trend of coastline advance (regression) and retreat (transgression) varies due to tectonically induced differentiated basin subsidence and the formation of river deltas such as the Yellow River, Haihe River, Liaohe River Delta, and natural, anthropogenically induced change in riverine sediment discharge to the Bohai Sea.

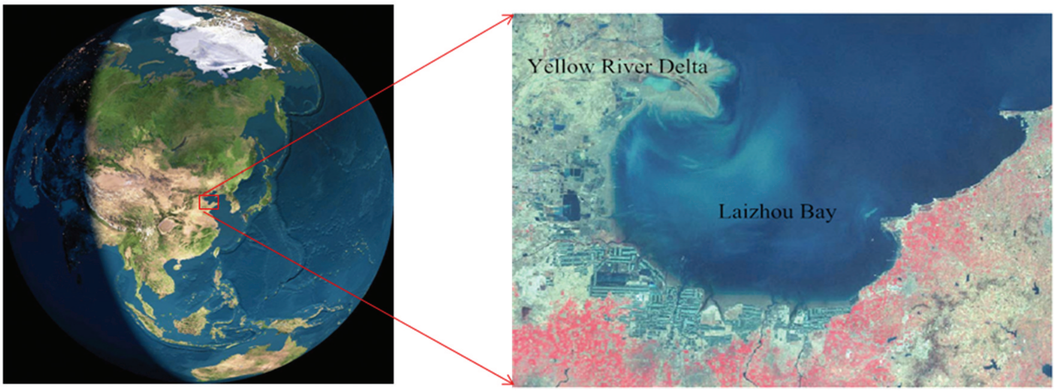

Figure 1. Study area: Laizhou Bay, Southern Bohai Sea, China
Maps of Asia and Bohai Sea from http://www.ngdc.noaa.gov/mgg/global/global.html; Laizhou Bay data from Landsat-5 TM satellite image, July, 2009

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In the Laizhou Bay, southern Bohai Sea, these processes can be studied exemplarily. The Bay is subdivided into three parts: Yellow River Delta (progradational sediment wedge), western and southern Laizhou Bay (muddy coastal embayment), and eastern Laizhou Bay (sandy to rocky coast).

The western-subsiding-part is dominated by the Yellow River delta and the discharge of the riverine particulate matter. By a counterclockwise current system fine-grain sediments are transported to the shallow coastal areas of the southern Laizhou Bay where also smaller rivers deliver their load to the Bay. The subsiding western basin-dominated by the delta-is separated from the eastern part of the Shandong Peninsula by the NNE striking Tan-Lu Fault. The eastern coast of the bay belongs to the East China uplifting belt (Li *et al.*, 1991) and is determined by Mesozoic granites and sandstones. Here besides river load the coastal sediments descend from the erosion of Mesozoic coastal rocks.

The coastal development in the Bohai Sea is determined by the Postglacial sea level rise having caused a transgression which reached its maximum during the Holocene Climate Optimum about 6 ka BP. After the maximal transgression a drop in the relative sea level most likely related to the Neoglacial cooling is recorded by proxy data in several key areas of the eastern and southern area of Chinese marginal seas (Pirazzoli, 1991). Figure 2 shows the coastline displacement in the southern Bohai Sea since the maximum transgression of 7000 a BP. The coastlines from 7000 a BP until 1128 AD are reconstructed from geological proxies. The 1891 AD coastline was derived from a historical nautical chart. This paleo-coastline information reflects dynamic coastal evolution varying at different time intervals, which provide essential input data for the model implementaion. River course shifting of Yellow River, and significant increase of Yellow River sediment discharge after 11 AD (Figure 3) may explain the phenomena of coastline displacement at the Laizhou Bay.

The Holocene regression after 7000 a BP reflects besides sea level drop the increase in the Yellow River sediment discharge. Figure 3 shows the paleo- and present sediment load supplied by the Yellow River to the Bohai Sea according to Wang *et al.* (2007). According to the data, the Holocene pristine sediment discharge measures about 0.1−0.2 Gt/yr. During the Zhou Dynasty due to deforestation the sediment discharge increased, and a high level of discharge was maintained by the Mid−20th century. The curve shows clearly the from about 1950 AD a decrease of sediment supply from 1.5 Gt/yr in 1950 to 0.2 Gt/yr in 2000 AD because of dam reservoir impacts, soil conservation practices and (natural) precipitation decrease. Also, the shifts in the subrecent outlets are a main effect of hydro-engineering.

Recent relative sea level changes are recorded by gauges' time series data from the western and the eastern Laizhou Bay from different geological settings. The mean relative sea level rise is about 2.1 mm/yr from 1950AD to 1994AD at the western subsiding coast (Yangjiaogou gauge in Figure 2), while there is a mean sea level rise of 1.7 mm/yr from 1950AD to 2010 AD at the eastern coast (Longkou Gang gauge in Figure 2). The reason for minor relative sea level rise values in the East of the Laizhou Bay is explained here by the uplifting tendency of the Shandong Peninsula (Li *et al.*, 1991). The shift in the tendency of sea level change from a decrease during the Late Holocene to the last decades along with diminished sediment supply by the Yellow River explains increasing erosional effects at the eastern delta area and in the Laizhou Bay.

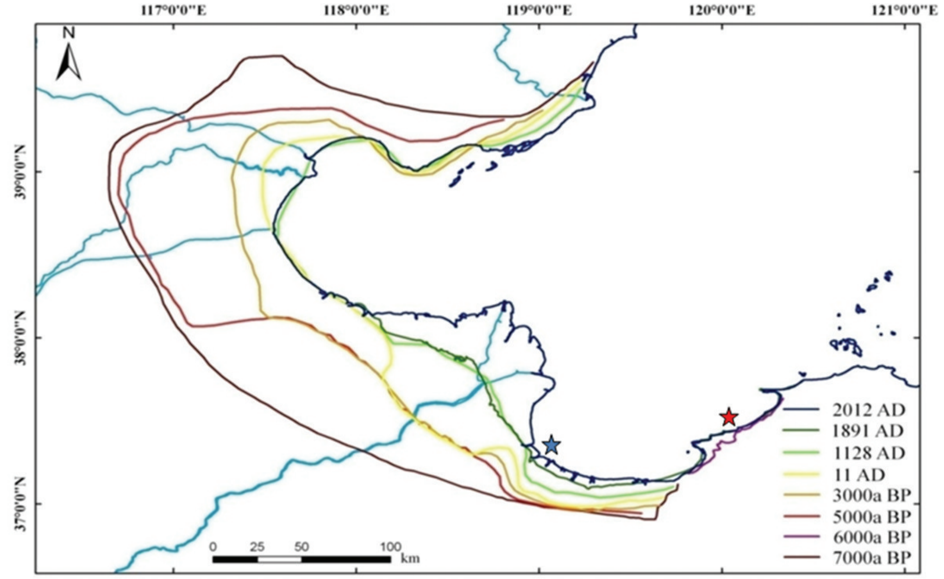

Figure 2. Ancient and recent coastlines of West Bohai Sea
2012 AD: Northwest Bohai Sea: nautical chart of Qinhuangdao Gang to Qihe Kou (Anonymous (1959−2009));
Southwest Bohai Sea: nautical chart of Qihe Kou to Longkou Gang (Anonymous (1958−2011))
1891 AD: R. C. Carrington of the Hydrographic Office, 1891; 7000a BP, 5000a BP−1128 AD: Xue (2009), 6000a BP: Zhuang (1987)
blue asterisk: Yangjiaogou gauge, red asterisk: Longkou Gang gauge

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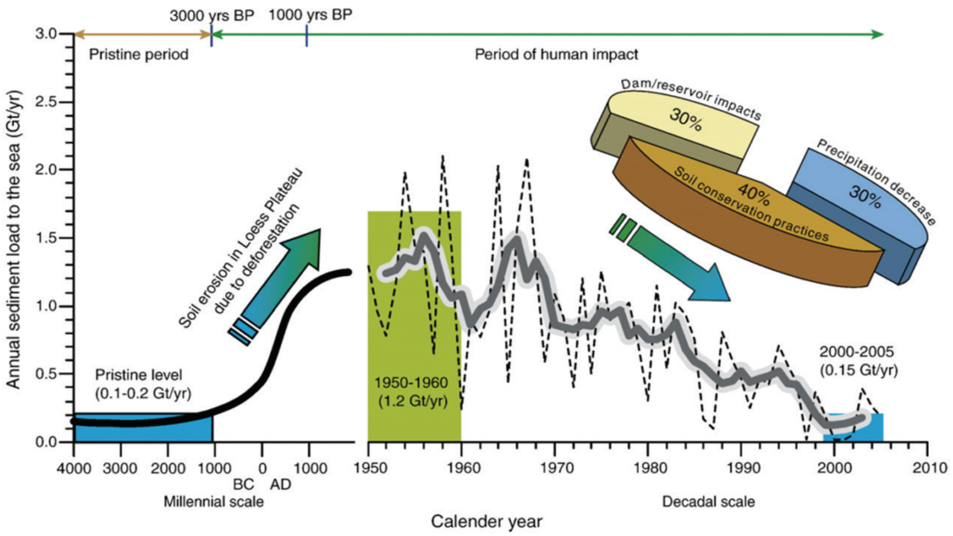

Figure 3. Past and present sediment load discharged from the Huanghe (Yellow River) to the sea (Wang *et al.*, 2007)

METHODS

General concept of morphodynamic modeling

The model is utilized to describe the change of a reference digital elevation model DEM_t during a time span Δt. It is taking into account the relative sea level change ($RSL_{\Delta t}$) and the change in sediment thickness because of accumulation and erosion of sediments ($SED_{\Delta t}$):

$$DEM_{t+\Delta t} = DEM_t + RSL_{\Delta t} + SED_{\Delta t}. \qquad (1)$$

This model has been applied successfully by Qi (2013) to reconstruct a paleogeographic scenario of the southwestern Bohai Sea. In the model the relation describing the relative sea level change $RSL_{\Delta t}$ plays a central role

$$RSL_{\Delta t} = EC_{\Delta t} + GIA_{\Delta t} + \sum_i E^i_{\Delta t} \qquad (2)$$

Symbols in eq. 1 and 2 represent 2D fields covering an area of investigation **R** with values allocated to vectors r marking any location in the area **R** (for instance $dem_t(r) \in DEM_t$, $\forall r \in \mathbf{R}$).

The relative sea level change is composed of different components, the eustatic (climatically driven) sea level change ($EC_{\Delta t}$), the glacial-isostatic adjustment ($GIA_{\Delta t}$) and minor effects $E^i_{\Delta t}$ as gravitational effect, compaction and others. For the historical reconstruction of paleo-digital elevation models, paleo-coastlines and RSL-data can be derived from interpolation of geological proxy-data pointing spatially to the position of ancient coasts or-for the younger history-from historical maps.

For a quantification of the $SED_{\Delta t}$ component in eq. (1) the so-called Dynamic Equilibrium Shore Model-DESM (Deng *et al.*, 2014) is applied. First, the area of research (model domain) is to be defined. For optimal parameterization it should be ensured that the area can be regarded semi-enclosed. Regarding the parameters, there are three of them of special importance: the relative sea level change during the time span of interest, the supply of sediments from external sources and the redistribution of sediments (budgeting) within the area of investigation.

Generalised description of the model DESM at the wave-dominated sandy coast

At the wave-dominated sandy coast, the model domain is a semi-enclosed area in terms of sediment budget, when lateral sediment in-flux $Q_{LST,in}$ (m^3) and out-flux $Q_{LST,out}$ (m^3) at the domain's lateral boundary is zero (i. e. $Q_{LST,in} = Q_{LST,out} = 0$) in Figure 4. The model domain of DESM consists of retreating and advancing coast segments. The whole model domain is thus discretized alongshore into n+m zones, each zone represented by one cross-shore profile (Figure 4). Based on recent DEM, for any time point $t \leqslant 0$, the depth of cross-shore profile representing each zone is described by the exponential function with the origin at the shoreline and the end point at the closure depth. Coastal bathymetrical profiles at the coastal erosion and accretion zones are described respectively as follow:

$$y = a(1 - \mathrm{e}^{(const1 * b_0)(x+\Delta c_t)}) - s_t,\ t \leqslant 0$$
$$y = a(1 - \mathrm{e}^{(const2 * b_0)(x+\Delta c_t)}) - s_t,\ t \leqslant 0 \qquad (3)$$

where y is the water depth (m) under the mean sea level and x is the offshore distance from the shoreline (m); a is the exponential limit of the profile; b_0 is the curvature coefficient of the present cross-shore bathymetrical profile; Δc_t is the known distance (m) between historical and present coastlines; and S_t is known relative sea level changes (m) compared with recent time 2000 AD ($t = 0$). The $const1$ and $const2$ are curvature coefficients. When $t = 0$, eq. (3) represents the recent coastal submarine profile.

At a given time t, the subaerial mass volumes can be estimated on a basis of the modern DEM and the data of Δc_t and s_t, as is given in Deng *et al.* (2014). At the semi-enclosed coast in terms of sediment budget for a given time t, the mass balanced mathematical expression can be given below:

$$\left| \sum\nolimits_{i=1}^{m} V_{erosion,i}(const1, \Delta c_{t,i}, s_{t,i}, b_{0,i}, a_i) \right| =$$
$$\left| \sum\nolimits_{j=1}^{n} V_{accretion,j}(const2, \Delta c_{t,j}, s_{t,j}, b_{0,j}, a_j) \right|,\ t \leqslant 0 \qquad (4)$$

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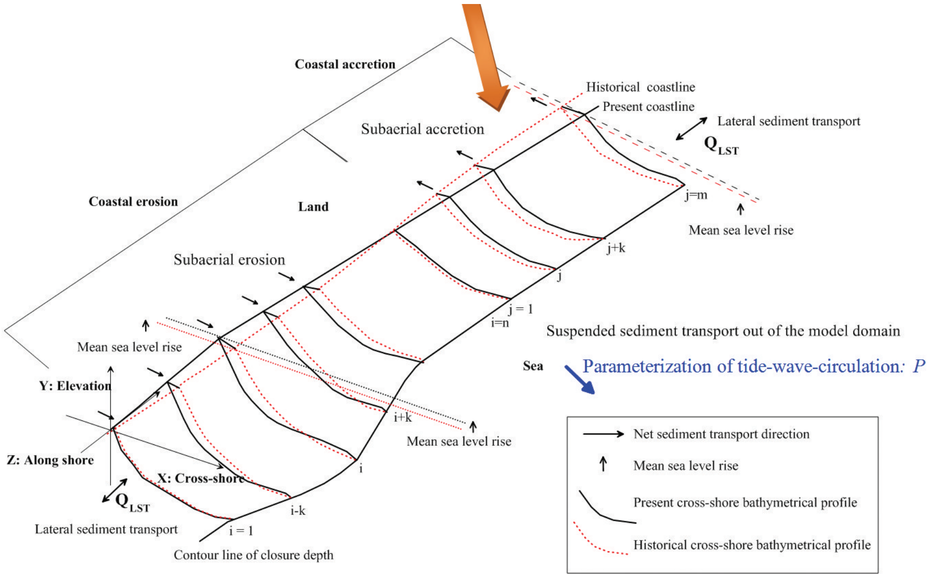

Figure 4. Sketch of a three-dimensional concept of the DESM model for coasts with river and tide influences

$V_{erosion}$ and $V_{accretion}$ are respectively erosion and accretion sediment mass volume (m^3), and subscript "i" or "j" denote the profile number in Figure 4. For a given time t, the data of a modern Digital Elevation Model, historical coastline changes, and relative sea level records can provide the information of parameters of Δc_t, s_t, b_0 and a for each profile i or j, hence, the only unknown parameters are *const*1 and *const*2. Eq. (3) can be thus simplified as:

$$\left| \sum_{i=1}^{m} V_{erosion,i}(const1) \right| = \left| \sum_{j=1}^{n} V_{accretion,j}(const2) \right| \quad (5)$$

In this equation, *const*1 is the uniform ratio between paleo – and present-curvature coefficients of all cross-shore profiles at the retreating coastal zones, and *const*2 is the ratio at the advancing coastal zones. Hence, by applying sediment mass balancing, the value of *const*1 can be determined by iterative inverse procedure when *const*2 is set to 1, or *const*2 can be calculated by iterative inverse procedure when *const*1 is set to 1. For the detail of this inverse modelling method, please see Deng *et al.* (2014).

Generalization of the model DESM to the river dominated muddy coast with influence of tide

To generalize the model at the muddy coast with the river mouth system, the seaward boundary is determined by the closure depth as well and at the alongshore direction it is bounded by the location of transition from coastal accretion to erosion. The subaerial mass volume can be estimated by using parameters of subaerial terrain heights, coastal retreat and advance distances and relative sea level changes, as like the examples given in Deng *et al.* (2014). In addition, the tidal flat, riverine sediment sources and the amount of them deposited at the model domain needs to be parameterized. This parameterization has been preliminarily described in Deng *et al.* (2014) in an abstract form. Here, a complete description is provided.

As like the model DESM, the whole coastal domain at the underwater part is discretized alongshore into m zones, each zone represented by one cross-shore profile (Figure 5). Based on the recent DEM, for any time point $t \leqslant 0$, the depth of cross-shore profile representing each zone is described by the exponential function with the origin at the shoreline and the end point at the closure depth. Coastal bathymetrical profiles at the coastal accretion zones are described as follow:

$$y = a\left(1 - e^{(const2 * b_0)(x + \Delta c_t - \Delta l_{tf})}\right) - s_t,\ t \leqslant 0,\ x \geqslant \Delta l_{tf}$$

$$y = -\frac{h_{tf}}{l_{tf}}(x + \Delta c_t) - s_t,\ t \leqslant 0, \Delta c_t \leqslant x \leqslant \Delta l_{tf} \quad (6)$$

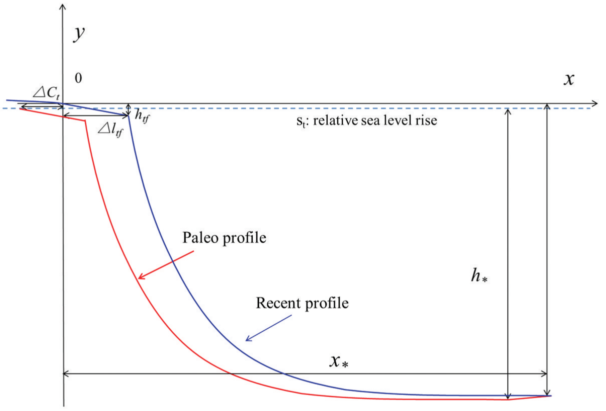

Figure 5. Sketch showing parameters for modeling coastal profile shapes (accretion type)

where y is the elevation (m) above the mean sea level and x is the distance (m) away from the shoreline where the elevation is zero; a is the exponential limit of the profile that remain un-

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changed with the time and Δl_{tf} and h_{tf} are respectively the width (m) and the deepest depth (m) of tidal flat that are assumed to be independent of the time; b_0 is the curvature coefficient of the modern cross-shore bathymetrical profile; Δc_t is the known distance (m) between historical and present coastlines; and S_t is known relative sea level changes (m) compared with recent time 2000 AD ($t=0$). When $t=0$, eq. (6) describes the recent submarine coastal profile. The *const*2 are the curvature coefficient reflecting the geomorphological changes.

The mass balanced mathematical equation can be expressed as follow:

$$P * V_{River} = \left| \sum_{j=1}^{n} V_{accretion,\,j}(const2, \Delta c_{t,\,j},\, s_{t,\,j}, b_{0,\,j}, a_j) \right|, \quad t \leqslant 0 \qquad (7)$$

In this equation, V_{River} is the sediment flux (m^3) from the river and P stands for the percentage of this flux controlling deposition at the model domain. P is a function of joint effects of wave, tide and current, which is derived from the process-based modelling experiments. For a given time t, the data of a modern Digital Elevation Model, historical coastline changes, and relative sea level records can provide the information of parameters of Δc_t, s_t, b_0 and a, hence, the only unknown parameters are *const*1 and *const*2. Eq. (7) can be thus simplified as:

$$P * V_{River} = \left| \sum_{j=1}^{n} V_{accretion,j}(const2) \right| \qquad (8)$$

*Const*2 is the uniform ratio between paleo and present curvature coefficients of all cross-shore profiles at the accreted coastal zones. By using the information of a modern DEM, historical coastline changes, and relative sea level records, eq. (8) describes how the coastal profile shape (i. e. *const*2) is determined by riverine sediment source V_{River} and hydrodynamic force P at the research area.

When the alongshore boundary is determined by the nodal points where lateral sediment flux is zero and the whole model domain includes the erosion and accretion coastal segments, then eq. (4) should be re-written as follow:

$$P * V_{River} = \left| \sum_{j=1}^{n} V_{accretion,\,j}(const2, \Delta c_{t,\,j}, s_{t,\,j}, b_{0,\,j}, a_j) \right| - \left| \sum_{i=1}^{m} V_{erosion,i}(const1, \Delta c_{t,i}, s_{t,i}, b_{0,i}, a_i) \right|, \quad t \leqslant 0 \qquad (9)$$

In this case, either *const*1 or *const*2 has to be assumed to equal to 1 so as to obtain the solution of Equation 5. The calibration procedure will be needed to decide which shape parameter needs to be set to 1. Variation of the riverine sediment sources V_{River} and hydrodynamic (i. e. wave, current and tide) force P induce a dynamic equilibrium evolution of coastal profiles, as is shown in Figure 6.

MODEL APPLICATIONS

Model setting

Historical coastline changes

For the historical coastline changes, the British map (R. C. Carrington of the Hydrographic Office, 1891) covering the whole Bohai Sea and north Yellow Sea (Figure 7) is used for the comparison. As can be seen in Figure 7, this map does not include, not proved any human constructions that can be used as the control points. The coordinates given in the map are regarded as control points. The projected map coordinate system is UTM zone 50 on WGS84 spheroid. As this map covers a large area, only local study area Laizhou Bay is geo-referenced by using first-order polynomial transformation method. The Root Mean Square Error (RMSE) is about 300 m. The lack of control points in the map makes the accuracy assessment and precise rectification rather difficult. But, the alternative assessment was conducted by measuring the width of coastline line (that is about 200 m) in the geo-referenced map.

The result of the comparison of coastlines in Figure 8 shows a rapid progradation of Yellow River Delta, and a relocation of Yellow River Mouth. The accuracy error is definitely not comparable to this magnitude of coastline changes, and this allows the application of the DESM model to quantify the sediment mass balancing. The model domain thus includes the Yellow River Delta and only the muddy coastal part.

Recent DEM

Figure 9 shows the recent DEM in 2000s that comprises the nautical chart data mainly measured in 2002 AD, the Shuttle Radar Topography Mission (SRTM) data for the land relief elevation, and the water line extracted from the Landsat satellite images in 1999 AD. According to the tidal table (http://app.cnss.com.cn/tide_search.php), the water line is at the mean water line that is regarded as the coastline in 1999 AD. Hereafter, the recent DEM is called 2000 AD DEM.

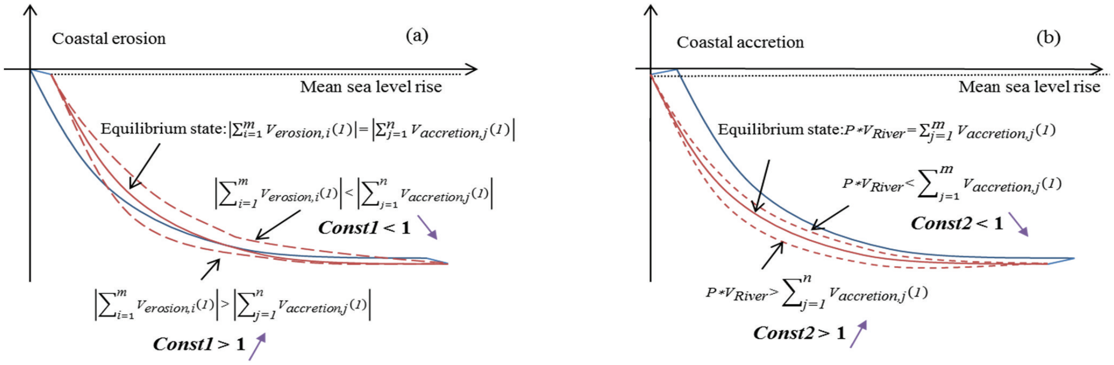

Figure 6. Examples showing how sediment sources and sinks affect coastal bathymetrical profile morphology in the DESM model for (a) semi-enclosed wave dominated sandy coast; (b) river-dominated coastal accretion area with influence of tide (Blue curve: present coastal profile; Red curve: paleo-coastal profile) (Modified from Deng *et al.*, 2014)

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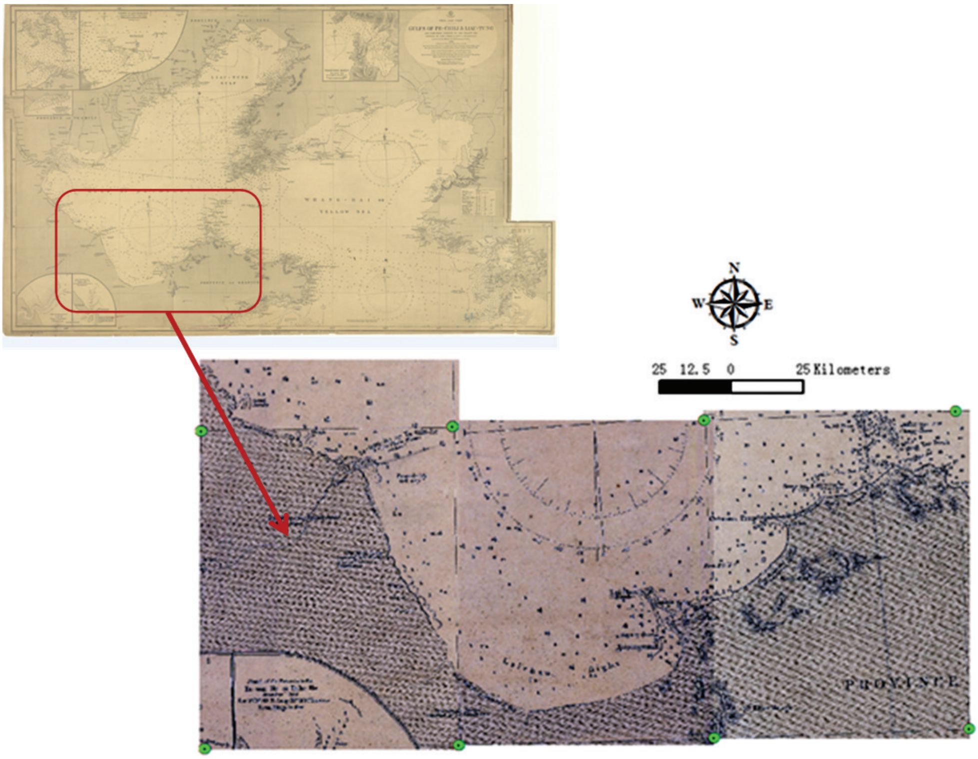

Figure 7. British map covering the whole Bohai Sea and north Yellow Sea (Control points marked as solid circle)

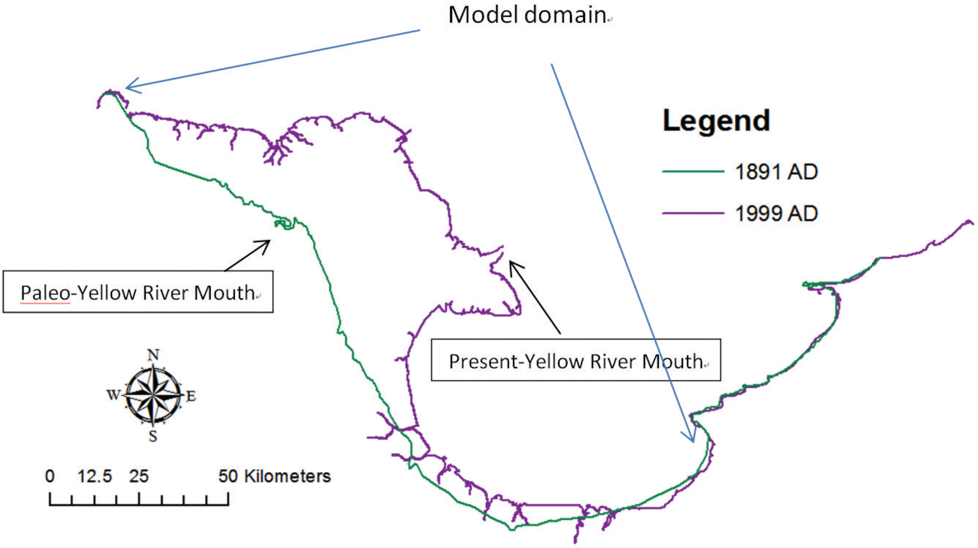

Figure 8. Comparison of coastlines between 1891 AD and 1999 AD

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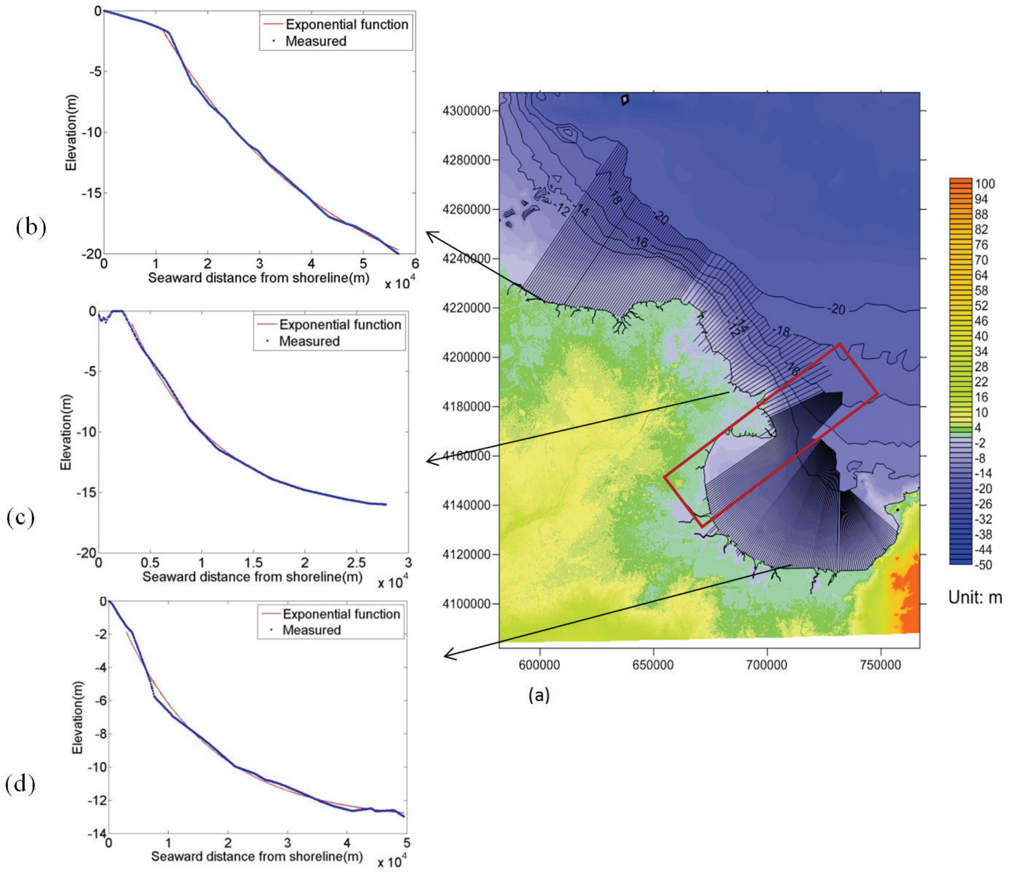

Figure 9. Discretization of model domain (DEM) and the three examples showing the fitness between exponential function and the bathymetrical profiles

The whole model domain depicted in Figure 8 is discretized into 242 zones alongshore with a uniform spacing of 1000 m. This long coastal section of 242 km length needs a changing value of closure depth along the coast, as the alongshore similarity of hydrodynamic forces is unlikely to remain. This is particular the case at the prograding River Mouth System where the closure depth should be the largest in front of the River Mouth due to the direct input of river sediment flux. Based on the morphological feature from the recent DEM (Figure 9), the 20 m isobath in front of the paleo-Yellow River Mouth seems to be the seaward limit of sediment progradation at the relatively flat sea bottom surface. Accordingly, the closure depth decreases eastward to 12 m (Figure 9a). Therefore, the artificial selection of alongshore variation of the closure depth to some extent follows the feature of sediment dynamic at the research area. The precise determination is not able to be done according to the current knowledge.

The fitness between the exponential function and the measured bathymetrical profiles below the tidal flat is tested by using R^2. The average R^2 of the 242 profiles is 0.96. There are three examples are given in Figure 9b, c and d. The tidal flat with the width up to several kilometers is assumed to be a linear surface whose boundary is defined as the 1.5 m isobaths that is almost able to distinguish tidal flat at all profiles based on the modern DEM in 2000 AD. For some examples of submarine profiles, please see Figure 9.

Sea level and river sediment discharge

Recent relative sea level changes are recorded by gauges' time series data from the western and the eastern Laizhou Bay from different geological settings. In Figure 10, gauge data of the western Laizhou Bay (Yangjiaogou) and eastern Laizhou Bay are depicted. The mean relative sea level rise is about 2.1 mm/yr from 1950 AD to 1994 AD at the western subsiding coast, while there is only 1.7 mm/yr from 1950 AD to 2010 AD at the eastern coast. The reason for minor relative sea level rise values in the East of the Laizhou Bay is explained here by the uplifting tendency of the Shandong Peninsula (Li *et al.*, 1991).

The Yellow River sediment flux decreases from up to $20 * 10^8$ t/yr in 1950s AD to ca. $0.2 * 10^8$ t/yr in 2005 AD at the Lijin station due to mainly anthropogenic influences (Figure 3). However, for the time span from 1891 AD to 2000 AD, the annual sediment load of 749 Mt/yr is adopted and the density of sediment is 1.36×10^3 kg/m^3 that is used for conversion to the volumetric unit. About 70% of this sediment load from the river deposited in the Bohai Sea, according to the wave-tide-circulation modelling study at the Bohai Sea and Yellow Sea that was carried out by Lu *et al.* (2013).

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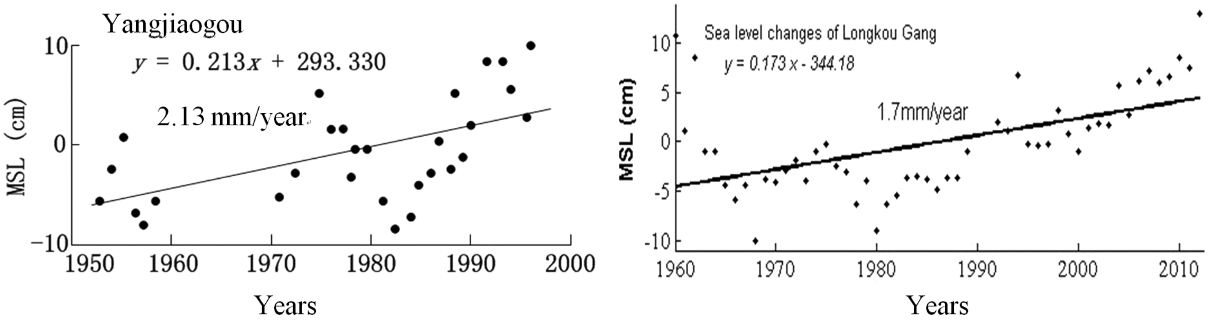

Figure 10. Sea level changes from gauge data of Yangjiaogou (SW Laizhou Bay) and Longkou Gang (E Laizhou Bay). For the location, please see Figure 2

Model results

After the iterative inverse procedure, the *const*2 in the Equation 2 is determined as 0.78. The output DEM in 1819 AD is compared with 2000 AD DEM in Figure 11. In this comparison, it shows a progradation process between 1891 AD and 2000 AD. The outcome of the model indicates a tendency direction of a dynamic equilibrium evolution of coastal sea bottom morphology. This tendency of coastal profile evolution coincides with the research by Liu *et al.* (2011) on the measured data of estuarine morphology.

We tested how changing river sediment flux influences the coastal morphological stability when the parameters of coastline changes stay unchanged. If the river sediment flux increases by ~40%, $P * V_{River} = \left| \sum_{j=1}^{n} V_{accretion,j}(1) \right|$ that means the coastal morphology is stable. Under this condition, the riverine sediment flux determines this morphological evolution. Figure 6 illustrates how river sediment flux affects dynamic equilibrium states of coastal profiles. If the river sediment flux is lower than the given value in the model setting, the value of *const*2 will be even smaller than 0.78. The smaller *const*2 means the present coastal profile shape would become more steeper than the paleo one, and vice versa (Figure 6). We also tested the sensitivity of the parameter of relative sea level rise. The double rate of sea level rise from 1891AD to 2000 AD can only accommodate additional 5% of the total sediment volume. In order to balance the sediment budget, the DESM model has induced a smaller *const*2 of 0.73 than 0.78. This smaller *const*2 also means a more steeper present coastal profile relative to the paleo one.

Yellow River sediment flux tends from Figure 3 to decrease in the future if anthropogenic activities continue in the upstream of the river, and the sea level rise is likely to be accelerated due to climate change and delta subsidence. The above model sensitive tests show that both boundary conditions of the sea level and river sediment flux are main driving factors for coastal morphology development. When assuming constant coastline changes in the future, it can be anticipated that the current tendency of river sediment flux and sea level change will not induce an equilibrium state of coastal morphodynamic evolution. On the contrary, it is likely that the coastal morphology will continue this tendency and will not have sufficient sediments to fill the increasing accommodation space because of the rising sea level. At the south and east of the Laizhou bay that is relatively far away from the Yellow River Delta, there are less sediments coming from Yellow River than the adjacent area of the river delta. The decreasing river sediment flux and rising sea level would make this area more vulnerable to erosion than the west Laizhou Bay that is just next to the Yellow River Delta. As the model can only reflect the aggregated effects, the model cannot describe the intermediate processes between 1891 AD and 2000 AD, such as river route shifts that may temporally influence the sediment transport pattern.

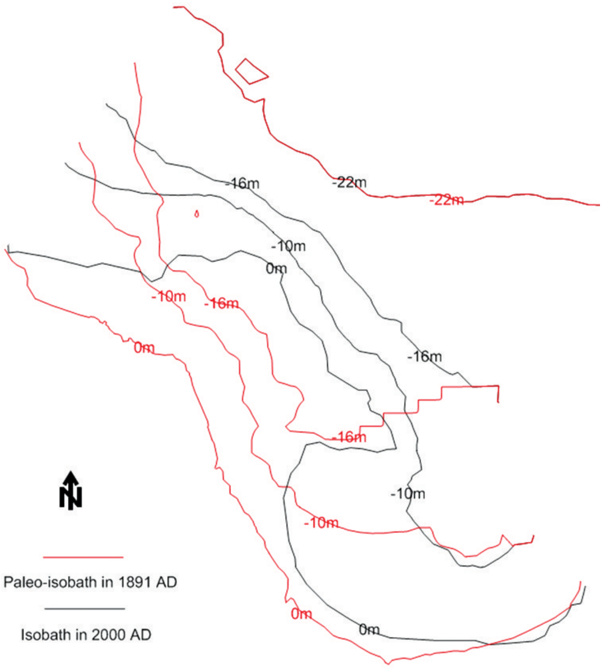

Figure 11. Isobaths comparison between 1819 AD DEM and 2000 AD DEM

DISCUSSION AND SUMMARY

River mouth systems play a key role for the generation of

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source-to-sink models describing the pathway of particulate matter discharged by the rivers to the ocean. The transformation of matter and energy in these zones of transition from the continent to the receiving marine basins depends on the dominance of the interfering main sources of energy governing the sediment dynamics: river (fluvial), tides and waves (Milliman and Farnsworth, 2013). During the younger Holocene the Yellow River Delta and the coastal zones within the vicinity are regarded a typical river dominated system with a prograding delta and a regressive sea in the easterly adjacent Laizhou Bay. The morphodynamic development of the river mouth system is well recorded by paleo-coastlines and for the younger history by historical maps. The progradation of the sedimentary system was even amplified by the Holocene sea regression.

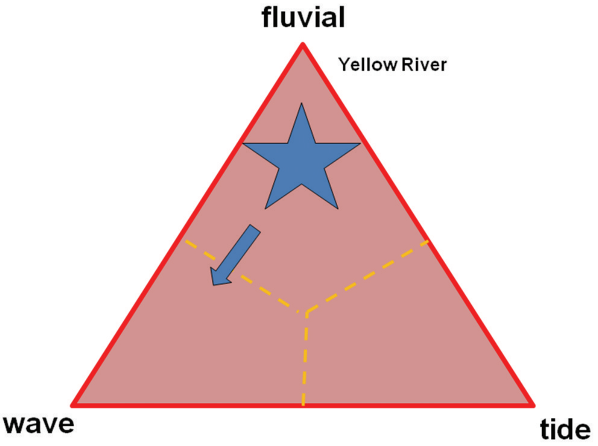

Figure 12. River mouth classification system by acting factors and current positions of the Yellow River Delta. The arrow marks a hypothetical anthropogenically triggered change of the natural environments

But, during the last decades a shift in the development of the coastal area is being recorded. The Yellow River mouth starves of sediment load since damming up-streams reduces the discharge of suspended matter to the Bohai Sea. So, the influence of wave and tide dynamics is replacing fluvial influences increasingly. Additionally sea level gauge data records a rise of the sea level simultaneously. Our investigation of waterline shifts supports the hypothesis of increasing coastal retreat in Laizhou Bay (Yan *et al.*, 2014). Moreover, our DESM model results have also demonstrated the future tendency of coastal retreat is likely to happen particularly at the south and east of Laizhou Bay.

According to this result, we have to recognize that after a period of Holocene regression the area undergoes probably a new period of sea transgression. This transgression is most probably due to the recent sea level rise as a result of modern global warming. A second reason has to be searched in the continuous decrease of riverine sediment supply. For the Yellow River delta we can formulate the hypothesis of a shift in the environment as depicted in Figure 12. This envisaged development would cause quite different conditions for the management of the delta and the coasts in its vicinity. In order to get closer to a realistic future projection new concepts in morphogenetic modelling have to be set up. Besides data about sea level change and river discharge variability, meteorological information about wind and wave climate and storm frequencies have to be involved into the analysis. Different data categories have to be made available. The scale spans from future climate modeling results to planning information about actions upstream the Yellow River valley steering the discharge of water and sediment supply. The DESM model (Deng *et al.*, 2014) has proved to provide reasonable scenarios as future projections of coastal developments of marginal seas. It is suggested to continue the study of coastal development of the Bohai Sea by applying the DESM model.

The complexity of the system to be studied requires interdisciplinaryand international co-operation. On the other side, the changing environmental conditions of river mouth systems turn out to become of global importance. So, comparative studies, in particular with marginal seas in low and high latitudes will help to understand functioning of river mouth and coastal systems.

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