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Earth observation-based coastal zone monitoring of the Yellow River Delta: Dynamics in China's second largest oil producing region over four decades

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ABSTRACT

The largest challenge for the Yellow River Delta region is finding an equilibrium between its two largest assets: large, valuable wetland reserves rich in biodiversity, declared as Ramsar sites in 2013 and breeding and resting grounds for numerous migratory bird species on the one hand, and extensive industrial and urban development based on the wealth of large underground oil and gas reserves, on the other. Based on high and highest spatial resolution satellite imagery covering nearly four decades, we employed manual feature digitization as well as rate-of-change statistics automatically derived with the Digital Shoreline Analyses System (DSAS) and present oil-industry-induced river bed changes and related coastal dynamics manifested via land erosion or accretion, and thus overall changes in the appearance of the Yellow River Delta. Over the past 37 years large re-diversions led to net erosion areas with over 13 km of shoreline retreat, and net accretion areas with over 21 km of shoreline advance. The satellite data furthermore enabled an assessment of oil pump development in the delta for the past two decades, indicating a strong expansion of oil extraction activities even in two of the delta's protected nature reserves, taking place at times and locations that indicate noncompliance with national regulations. Overall, the study proves the power of satellite imagery to quantify changes in the coastal zone, and to detect industry related activities; including the monitoring of compliance to restricting regulations. It is especially the freely accessible Landsat archives, granting four decades of monitoring, which are of immeasurable value to depict the regions dynamics. With Landsat 8 already in orbit and with the upcoming launch of the Sentinel-2 satellite, the monitoring concept presented here can be continued into the future.

Introduction

River deltas globally are home to many of the most valuable wetland ecosystems on our planet, but are increasingly susceptible to ongoing change induced by socio-economic transformation and climate change (Kuenzer & Renaud, 2012). Clear locational advantages of river deltas include a flat terrain, fertile alluvial soils, abundant to fresh- and salt water resources, as well as a connection with the hinterland defined by the whole basin of the respective rivers. Therefore, deltas are a preferred location for human livelihoods, as the regions offer good conditions for settlement, ice free harbors and the establishment of water and land based transport networks, ground for monoculture or industrial crops and aquaculture, as well as access to rich wetland biodiversity and recreational space. Furthermore, many deltas host vast underground resources of oil and gas, and salts. Although delta areas only comprise 5% of the global land area, over 500 million people live here, and Yangtze, Ganges, and Nile Delta alone held a population exceeding 230 million people in the year 2000 (Overeem & Syvitski, 2009). At the same time deltas and their wetland flora and fauna underlie severe stresses. Urban and industrial sprawl, resource extraction, as well as further socio-economic transformation lead to increased surface sealing, the spread of infrastructure at the cost of

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natural areas, ground compaction, the accumulation of solid and fluid wastes, as well as changes in water flow. Upstream irrigation, water diversion and sediment loss due to hydropower dams alter deltas erosion and accretion balances. Simultaneously, climate change induced sea level rise threatens the near coastal human livelihoods and natural habitats. Whereas in many developed countries local and national authorities and planners consider scenarios of coastal retreat and the extension of flood retention space, especially in developing and emerging countries delta ecosystems are often exploited far beyond sustainable limits (Renaud et al., 2014). Be it the severe loss of mangrove ecosystems in the Mekong or Dong Nai River Deltas (Kuenzer & Vo, 2013; Vo, Oppelt, & Kuenzer, 2012), severe land subsidence in the Chao Pharya or Yantze Delta (Chen & Zong, 1999; Trisirisatayawong, Naeije, Simons, & Fenoglio-Marc, 2011), the devastating pollution induced by the oil industry in the Niger Delta (Kuenzer, van Beijma, Gessner, & Dech, 2014), or upstream water diversion threatening water supply in the Godavari Delta (Bharati, Anand, & Smakhtin, 2009): river deltas experience a multitude of pressures. Delta resources need to be tapped in a sustainable way and biodiversity needs to be protected. However, to do so, stakeholders, politicians, and local decision makers need to have access to high-quality information depicting a river delta's dynamics. Many river deltas globally – especially when located in developing or emerging countries – can be considered data poor regions, or have not been fully investigated with respect to ongoing societal and environmental change. One such delta, where spatial information for informed decision making is urgently needed, is the Yellow River Delta in China.

Study area and scope of this paper

The Yellow River Delta is the place where the Yellow River meets the Bohai Sea. (Fig. 1) It is the vulnerable end of a river that has a total stream length of 5464 km and the highest erosion rate worldwide. The Yellow River is the second longest river in China, but it contributes only 2% to the total runoff of all rivers in China. Its basin covers an area of 795,000 km^2, hosting a total population of 107 million people and containing 12 million ha, some 17%, of China's cultivated agricultural land. The furthest upstream area of the Yellow River (Huang He) is characterized by complex terrain and deeply incised valleys, followed by the Gobi Desert and Loess Plateau in the middle reaches, where the river collects 90% of its sediments. The average annual sediment inflow to the broader downstream area is 1.6 billion tons (35 kg/m^3), of which a large proportion is deposited in the region furthest downstream: the Yellow River Delta. (Eryong et al. 2009; Wang, Ren, & Tan, 2007; Xu, Peng, Xu, Xiao, & Benoit, 2009; Zhang, Wen Huang, & Chong Shi, 1990). The high sedimentation rate causes an extraordinarily high spatio-temporal dynamic, which is reflected by the relocation of the river bed over ten times only since 1855, including a frequent shift of the river mouth location. The mesotidal Yellow River Delta spans an area of 10,000 km^2 and hosts a delta population exceeding 6 million people, including the more than 2 million inhabitants of the city of Dongying, located within the delta's reaches. The district containing most of the Yellow River Delta is Dongying District, which is part of the coastal province of Shandong (95 million inhabitants). The Yellow River Delta's destiny will be determined by how the two major assets the region has to offer are managed (Jiang, Deng, Zhan, & Yan, 2011).

On the one hand the delta comprises large wetlands hosting a rich biodiversity and a habitat for 1917 animal and plant species as well as 269 bird species, and an importing resting place for migrating birds, including about 152 protected species. The soils in these delta wetlands are highly affected by salinity, and about 70% of the delta is considered saline land (Shi & Zhang, 2003).

Vegetation composition contains many halophytic grass and shrub species (Fan et al., 2011; Zhang & Zhao, 2010), and tamarisks, seablites, and reeds are common (Xiang, Cheng, Hao, Xia, & Liu, 2010; Zhang et al. 2011). Two nature reserves that cover an area of about 145,000 ha and form the second largest coastal wetland in China were established in the Yellow River Delta area in the early 1990s, and were declared Ramsar wetland sites in 2013. Every year the region attracts many tourists who enjoy the wetland landscapes and especially bird-watching, and eco-tourism is on the advance (Cui, Yang, Yang, & Zhang, 2009).

Fig. 2 depicts the location of the two national nature reserves in the Yellow River Delta, which together comprise an area of 145,000 ha. The northern reserve is located around the floodplains and abandoned former river mouth in the northern delta and contributes 40,000 ha to the overall reserve, while the eastern reserve is located in the floodplains of the active river mouth and is about 105,000 ha in size. The reserves were approved by the Dongying government in 1990 as local nature reserves, becoming provincial reserves in November 1992, and approved as national nature reserves by the State Council of China in October 1992 (Fang & Xu, 2000). Each of the two reserves consists of a core zone, a buffer zone and an experimental zone (see Fig. 2). Within the zones, different types of activities are allowed (see Table 1). According to the management regulations of national natural reserves as specified by the State Council of China, any kind of human activities in the core zone of reserves is forbidden.

On the other hand, the Yellow River Delta is part of the Shengli oil field (>4.6 billion tons reserves), China's second largest oil field, and the delta is home to the productive local Gudong oil field (see Fig. 2).

Oil is extracted on- and off-shore on both sides of the river mouth in amounts exceeding 800,000 barrels/year. It is these oil resources that – up to the present – have shaped the destiny of Dongying district (Bi, Wang, & Lu, 2011). Oil was discovered in the mid-1960s and the retort city of Dongying was established soon thereafter in 1983 as a home base for oil related companies and workers. Oil and gas mining operations run at elevations below 1 m above sea level, protected by river and sea dykes of intermediate standard. Numerous oil pumps are located in sensitive wetland areas, which are resting and breeding ground for numerous migratory bird species (see Figs. 3 and 4). Oil related infrastructure in the delta is not well maintained, and leakage and spills are common. This also affects the local food chain, as river branches, wetland pools, and the coastal waters are common grounds for fish and clam collection. Surface water is used for aquaculture and irrigation, and some rural poor even rely on river mouth water as a directly source of their domestic water supply. Subsidence due to oil and water extraction as well as due to heavy structures compacting the ground is commonplace (Higgins, Overeem, Tanaka, & Syvistski, 2013; Ottinger, Kuenzer, Liu, Wang, & Dech, 2013). This aggravates the natural Quarternary neotectonic subsidence of 5 mm/year. Sea level rise, which is projected to rise for 35 cm by 2050 (Lewis, 2009; Nicholls, 2004), as well as a decrease in the amount of sediment reaching the delta, due to upstream hydropower facilities like the Xiaolangdi Dam, further amplify this process. Coastal erosion and a steady demand for dyke elevation, as well as salinity intrusion further inland will be the consequence (Liu, Sui, & Wang, 2008; Qiao et al. 2010).

The overall main challenge for decision makers and stakeholders involved in local planning in the delta district of Dongying is to find a sustainable equilibrium between economic development on the one hand, and the protection of natural wetlands of rich biodiversity on the other (see Figs. 3 and 4). They are in urgent