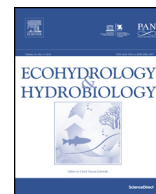




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Original Research Article

An overview of ecohydrology of the Yellow River delta wetland

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ABSTRACT

The combined effects of geophysical and ecological processes, such as water and sediment load, land use change, eustatic sea level rise, land subsidence, and wetland loss, have produced a dynamic eco-hydrologic environment of the Yellow River delta (YRD) in northern China. Recent changes due to socio-economic forces and climate change have threatened the status of YRD wetland as important habitats of endangered species of wild birds and hatchery of aquatic animals on the brink of extinction. This review demonstrates that water-sediment regulation scheme (WSRS) in the last 10 years has brought some ecological benefits to the wetlands, but more recent observations have indicated diminishing effectiveness of the engineering projects. Although research has been conducted to monitor, evaluate, and predict the ecological and hydrological conditions of the YRD, tremendous knowledge gaps still exist for the sustainable management of the YRD for multiple objectives of natural reserve, energy extraction, and agricultural production. Therefore, ecologists and hydrologists should work together with social scientists and policy makers to develop a holistic plan that not only maintains the ecological integrity but also improves the livelihood of people in the YRD.

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1. Introduction

The Yellow River delta (YRD) in northern China has received increasing attention from scientists, engineers, and environmental planners because of its critical role in wildlife protection, energy production, and agriculture. The YRD has the largest and youngest coastal wetland ecosystem in China, providing habitat for millions of wild birds and serving as spawning and nursery grounds for numerous freshwater and marine organisms (Cui et al., 2009; Kong et al., 2015; Ma et al., 2014). In addition, tremendous values of ecosystem services including

nutrient cycling, carbon storage, as well as tourism and recreation are provided by the YRD wetlands (Yu et al., 2011, 2012). Economically, YRD has the second largest oil field in China and the energy production and related industrial activities have caused enormous impact on the surface and subsurface environment in the region (Kuenzer et al., 2014). Agricultural production has occupied a large fraction of the newly formed delta lands and utilized substantial amount of riverine and underground freshwater resources (Han et al., 2014; Xu et al., 2002).

Like many of the large deltas around the world (Blum and Roberts, 2009; Syvitski et al., 2009), the YRD is facing increasing risks of degradation due to anthropogenic and natural forces (Bi et al., 2014; Cui et al., 2009; Gao et al., 2014; Kong et al., 2015; Wang et al., 2007). The fundamental changes in land-building and land loss in

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the YRD plain are rooted in the supply of water and sediment from Yellow River that undergone major shifts in the river's course since the delta's formation in 1855. Superimposed on the natural processes, population growth, oil and gas extraction, and agricultural development have placed enormous demands on the land and water resources and modified the delta's natural geologic, hydrologic, and ecologic systems. Furthermore, global climate change and sea level rise has modified ecohydrological processes within the delta and the effect is expected to intensify in the future (Wang et al., 2006). The objective of this article is to identify the knowledge gaps and future research needs of wetland ecohydrology in YRD based on a comprehensive review of literature.

2. A changing ecohydrological environment of YRD wetland

Several comprehensive overviews of the historical development of the YRD has been conducted in the last few decades (Li et al., 1998b; Liu et al., 2004; Saito et al., 2001; Xue, 1993; Yu et al., 2011). Briefly, the Yellow River is the second largest river in China with a total drainage area of 794,712 km² and a total length of 5464 km (Bi et al., 2014). As shown in Fig. 1, the river originates from the Tibet Plateau and flows through Loess Plateau and the North China Plain. The Yellow River has carried tremendous amount of sediments both to the northeast Bohai Sea and to the southeast Yellow Sea during the Holocene (Zhou et al., 2014). The modern YRD has formed since the mouth of the Yellow River shifted north in year 1855. The tremendous sediment load from the Yellow River has resulted in a complex deltaic environment. In the last 160 years, the main channel of the Yellow River has shifted courses 11 times and has built out a series of deltaic wedges into the nearby Bohai Sea. Collectively, sediment deposition at the mouth of Yellow River have produced eight overlaid distributary lobes with the active lobe developing around the Qingshuigou channels formed in 1976. The delta plain covers an area of 7870 km² with average deposition thickness around 15 m (Bornhold et al., 1986; Wang et al., 2012). The hydrodynamics near Yellow River mouth is dominated by semidiurnal tides (tidal range around 1.5–2.0 m) and wind driven waves and residual currents (Bi et al., 2014). For the groundwater system of YRD, Gao et al. (2014) divided coastal wetlands into groundwater seepage zone, tidal-induced transitional zone, and tidal zone, where the influence radius of oceanic tide is approximately 12–18 km. Integrated study on the interaction between freshwater inflow, sea water, and groundwater is urgently needed for the understanding of the hydrological processes of the YRD wetland.

With annual average rainfall of 590.9 mm and potential evaporation of 1962 mm, the YRD has a typical water limited environment where water resources need to be supplemented by river discharge and groundwater extraction (Kong et al., 2015; Newman et al., 2006). Over the past 60 years, construction of hydraulic structures and dramatic landuse changes in the Yellow River watershed has converted the second longest river in China to a hydrologic system highly regulated by human activities (Li et al.,

1998a). Hydrological circle of the Yellow River Delta (YRD) has undergone a series of regime shift, characterized by 70–90% reductions in water and sediment supply (Wang et al., 2007; Yu et al., 2013), which is similar to many other large deltaic systems in the world (Blum and Roberts, 2009; Syvitski et al., 2009). The downward trends in runoff were also caused by climate change and increased water consumption in the Yellow River Basin (Xu, 2003). The downstream Yellow River experienced serious drying up events from 1991 to 1999 with a maximum of 226 no flow days in 1997. Since 2002, watershed scale water-sediment regulation scheme (WSRS) was operated annually by the Yellow River Conservancy Committee (YRCC) with the objective of restoring ecohydrological conditions downstream (YRCC, 2014). During the period of WSRS operation (around 15–20 days), approximately 28% of the river runoff and 57% of sediment load was rapidly discharged through controlled release from the Xiaolangdi Reservoir. This abrupt change of flow and sediment pattern has caused substantial change of the morphological patterns (Bi et al., 2014; Wang et al., 2010) and landscape patterns (Li et al., 2009) of the YRD. However, the dynamic biological and ecological response of YRD wetlands to water and sediment discharge pattern were not adequately studied due to the lack of long term monitoring data and well-designed experiments (Sun et al., 2010).

Sea level rise (SLR) due to global change and land subsidence caused by extraction of groundwater and hydrocarbon has further jeopardized the health of YRD. In year 2012, the eustatic mean sea level (MSL) of the Bohai Sea has risen to 110 mm above the historical level (China Sea Level Bulletin, 2012). The MSL of Bohai Sea has shown an accelerated rising trend with a mean linear rate of 3.8 mm/year, which is higher than the global and national average. It is projected that the mean sea level of the Bohai Sea will rise another 68–140 mm by 2040 (Pelling et al., 2013). Rates of land subsidence in the modern YRD might exceed the rates of sea level rise due to natural compaction and consolidation, urban construction, underground water and brine withdrawal, and oil extraction (Higgins et al., 2013; Zhang et al., 2015). The results of InSAR time series analysis revealed the spatial pattern of widespread land subsidence in the modern YRD and reported an average subsidence rate of –5.1 mm/year (Zhang et al., 2015). Subsidence rates as high as 250 mm/year has been observed in selected areas and extraction of deep groundwater has been recognized as the dominant cause. The comprehensive study of Syvitski et al. (2009) has listed YRD as a delta in greater peril with a relative sea level rise of 8–23 mm/year due to sediment load reduction, sea level rise, and land subsidence. It shows that 1430 km² of the YRD is under threat of storm surge. As relative sea level rising much faster than delta-plain construction, the YRD has already experienced significant erosion and the overall area of YRD decreased since year 2000 (Kong et al., 2015). A series of engineering structures including dikes, levees, groins, and roads were built along the coast of YRD to protect agricultural and industrial facilities (Zhang et al., 2015). Those engineering construction were the main factor that slowed down the coastal erosion of YRD. However, concrete construction has severely altered

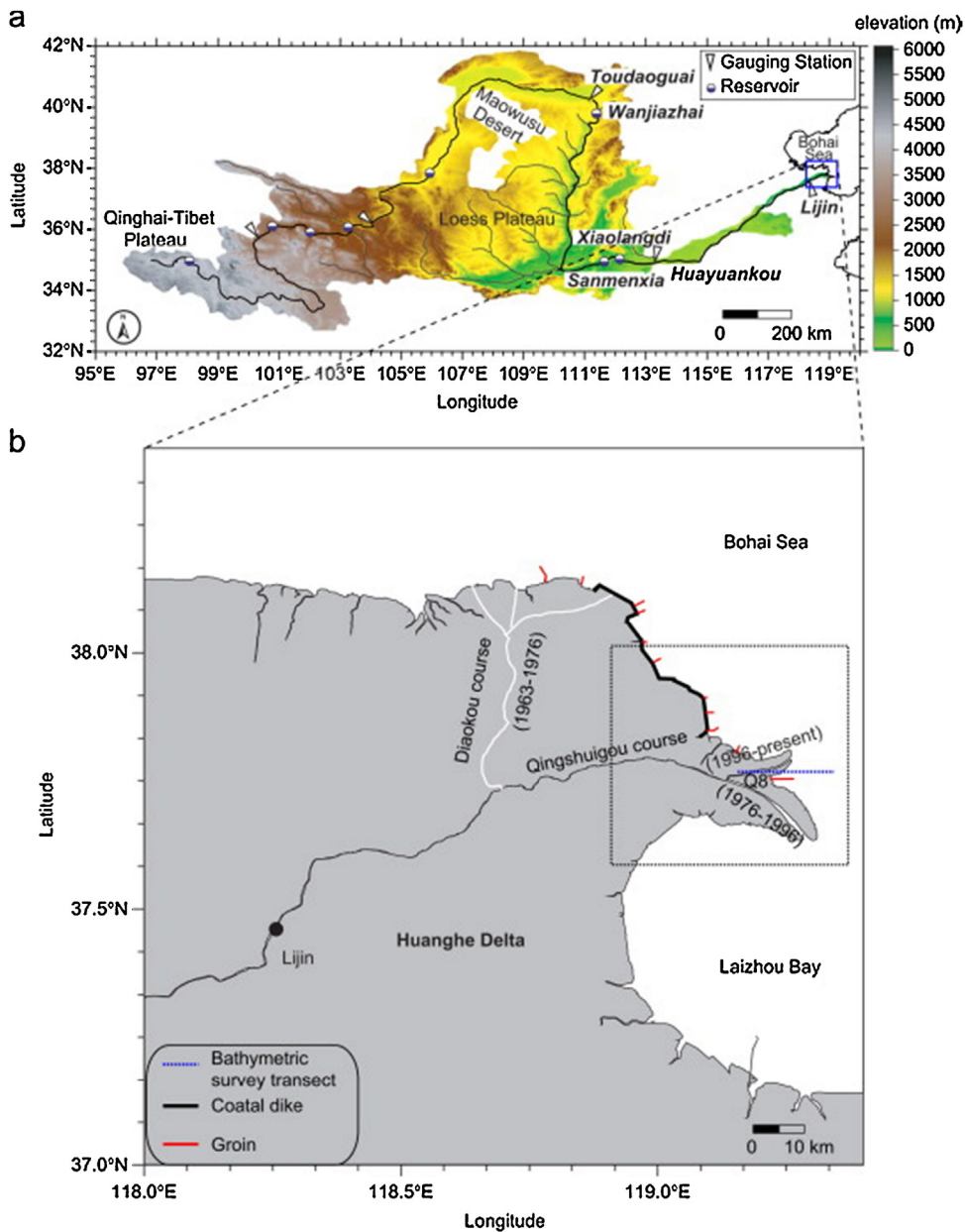


Fig. 1. (a) Map of the Yellow River drainage basin, showing the locations of major gauging stations and reservoirs in the main stream. The Yellow River is divided into the upper, middle and lower reaches by the Toudaoguai and Huayuankou gauges. (b) Map of the Yellow River delta showing the migration of the Yellow River deltaic river channel since 1976. The dashed rectangle in panel (b) indicates the location of the active Yellow River delta lobe. Reproduced with permission from Bi et al. (2014).

hydrologic cycle and may cause substantial negative impact to biodiversity and associated ecosystem functions (Gao et al., 2014). Systematic studies are urgently required to study the hydrological evolution of YRD wetland driven by sea level rise, land subsidence, and coastal construction.

3. Wetland degradation and restoration

The YRD wetland supports abundant biodiversity and is home to 220 seed plant species such as endangered wild soybean (*Glycine soja Siebold & Zucc.*), more than 800 wild

animal species, and 283 bird species, many of which are listed as endangered species (Cui et al., 2009). It provides an important habitat and transfer area for millions of migrating birds, such as the red-crowned crane, hooded crane, Siberian crane, oriental stork, black stork, and golden eagle (Wang et al., 2014; Xu et al., 2002). It is reported that wetlands covered an area of 4167 km² in YRD (Fig. 2), including 3131 km² of natural wetlands (swamps, marshes, tidal mudflats, rivers, lakes, etc.) and 1036 km² of artificial wetlands (rice fields, aquaculture ponds, channels, et al.) (Qi and Luo, 2007). The predominant native

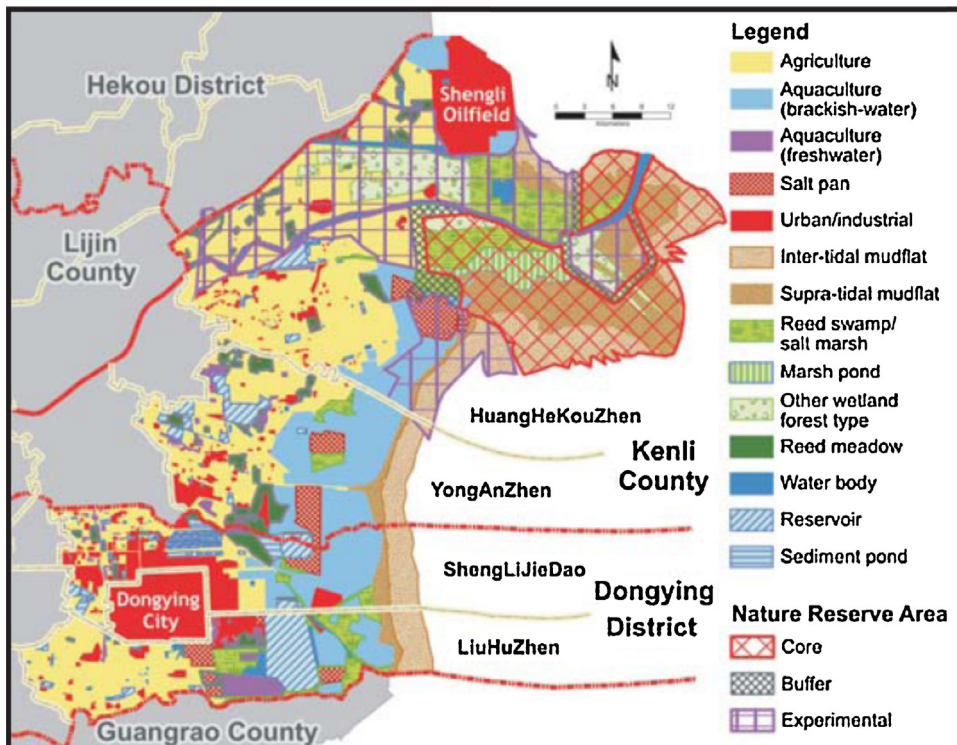


Fig. 2. Land use map showing the distribution and types of wetlands in the Yellow River delta. Reproduced from the WorldFish Center (2010).

vegetation are salt tolerant plants and aquatic plants including *Suaeda salsa*, *Phragmites australis*, *Tamarix chinensis* Lour., *Aeluropus sinensis* and *Imperata cylindrica* (Linn.) Beauv (He et al., 2007). A frequent succession among vegetation communities exists in the newly created wetlands (Yue et al., 2003). Soils of the YRD wetland are classified as Calcaric Fluvisols, Gleyic Solonchaks and Salic Fluvisols according to Food and Agriculture Organization (FAO) system and often have high salinity, low nutrient content and low organic matter (Yu et al., 2014). The vegetation type and soil properties (e.g., salinity, organic matter) often demonstrate a spatial pattern that can be related to the distance to the Yellow River course and the gradient from sea to land (Li et al., 2009; Yu et al., 2014, 2012). Soil salinity increased and organic content decreased in some areas owing to improper cultivation on lands that are not suitable for crop production (Xu et al., 2002; Yu et al., 2012). In addition, elevated concentrations of heavy metals, polycyclic aromatic hydrocarbons (PAHs), petroleum hydrocarbons, and pesticides have been observed in soil and plant samples, potentially caused by energy and chemical industries (Li et al., 2014; Yuan et al., 2014; Zhu et al., 2015). Overall, the ecological evolution of this newly created wetland and its interaction with climate and hydrology were not well understood due to the scarcity of long term monitoring data of the soils, plants, and animals.

The wetland ecosystem is seriously stressed due to depleting water resources, degradation of soil quality, water pollution, and agricultural and industrial activities in the YRD. The reed marsh, meadow, and tidal wetland

decreased by 17%, 37%, and 38%, respectively, from 1986 to 2001 due to decreased runoff and sediment load and conversion to aquacultural ponds and agricultural fields (Li et al., 2009). Construction of oil wells and roads has decreased landscape patch connectivity (Yue et al., 2003). As a result, the areas of red-crowned crane habitat decreased by 5935 ha from 1992 to 2008 (Wang et al., 2014). In addition, coastal construction and aquaculture activities might have destroyed the habitat of many wild species of aquatic organisms. Despite the lack of monitoring data, circumstantial evidences show that there are severe decreases in bird populations, sharp decrease in indigenous plant communities accompanied by increasing population of invasive species.

Wetland restoration projects have been initiated since the start of new millennium in order to prevent the wetlands from further deterioration and to protect endangered birds (Cui et al., 2009; Wang et al., 2014; Yang, 2011). Through WSRS operation, freshwater totaling $1.0 \times 10^8 \text{ m}^3$ have been allocated from Yellow River to the wetlands through a set of reservoirs and channels in July or August to ensure the supplement of sediment. Dikes have been constructed along the seashore to prevent seawater intrusion. The freshwater replenishment had significantly improved the structure and function of wetland ecosystem as indicated by rising water table, improving soil quality, increasing plant cover, and return of migrating and breeding birds by 2007 (Cui et al., 2009). However, recent surveys suggest that operations at current level may not be sufficient to fully

restore the plant and bird communities. A systematic review and assessment of the management practices of the YRD wetlands is urgently needed before further degradation of the ecosystem health (YRCC, 2013).

4. Concluding remarks and outlook

Although large amounts of researches have been conducted to study the evolution of YRD and its wetland ecosystem, this review of recent literatures shows that tremendous knowledge gaps still exist on the dynamics of ecohydrology of YRD wetland, especially the impacts of large scale anthropogenic activities including oil and gas production, agricultural development, as well as sediment and water regulation. From the ecohydrological perspective, we recommend to carry out following studies: (1) Interaction between river flow, sea water, and groundwater analyzed through in situ monitoring and modeling; (2) Biological and ecological response of wetlands to different water and sediment regimes studied by well-designed plot experiments; (3) Ecosystem health assessment based on comprehensive field data of water, soils, plants, birds, and aquatic organisms; (4) Future projection of the change of YRD wetland system due to climate changes and anthropogenic forces. However, it should be emphasized that the current issues in YRD wetlands are deeply connected with the regional socio-economic status. Competition for limited land and water resources by industrialization and urbanization has become the dominant stressor of the wetland ecosystem. Therefore, a cross-disciplinary discussion and policy development is essential to restore ecological integrity and improve livelihood of people in YRD.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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