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Impact of water diversion on the hydrogeochemical characterization of surface water and groundwater in the Yellow River Delta

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A B S T R A C T

The Yellow River Delta is undergoing severe ecosystem degradation through salinization caused mainly by seawater intrusion. The Yellow River diversion project, in operation since 2008, aims to mitigate a projected ecosystem disaster. We conducted field investigations across three ecosystems (Farmland, Wetland and Coast) in the delta to assess the effectiveness of the annual water pulse and determine the relationships between surface water and groundwater. The chemical characteristics of the groundwater in Farmland exclude the possibility of seawater intrusion. The Wetland is vulnerable to pollution by groundwater discharge from Farmland and to secondary salinization caused by rising water tables. The salinity values of groundwater at Coast sites likely reflect the presence of seawater trapped in the clay sediments, a premise corroborated through measurements of groundwater levels, stable isotopes and major ion signatures. Our δD–$\delta^{18}O$ two-dimensional graphic plot demonstrated that groundwaters of Farmland and Wetland changed toward more depleted isotopic compositions following water diversion, but this was not the case in the Coast sites, where the water table varied little year-round. A hydrochemical facies evolution diagram (HFE-D) demonstrated that freshening is taking place in the largest portions of the aquifers and that, without sustained water diversion recharge, these underground water bodies may switch from freshening to salinization on a seasonal time scale. Thus, the qualities of waters in coastal aquifers in the Yellow River Delta are substantially influenced by the process of ecological water diversion, and also by land use practices and by the lithological properties of the drainage landscape.

1. Introduction

Many of the world's largest deltas are densely populated and heavily farmed (Syvitski and Saito, 2007; Single, 2008). Yet most deltas are becoming increasing vulnerable to flooding and conversions of their land to open ocean as sediment compacts and sinks following the removal of oil, gas and water from underlying aquifers (Syvitski et al., 2009). Aquifer salinization through shifts in the fresh-saline water interface is one of the major threats to coastal ecosystems (Russak and Sivan, 2010). Shifts are controlled by a suite of natural and man-made mechanisms, such as major storms at sea (Andersen et al., 2005), fluctuating tide levels (Wang and Tsay, 2001), global rise in sea level (Post, 2004) and recharge by surface water pulse (Sivan et al., 2005).

The complexity of delta dynamics and the imperative for sustainable management requires a full understanding of hydrological function in each of the component ecosystems (Acreman, 2000; Gilvear and Bradley, 2000; Winter et al., 2001). The ecosystems of Yellow River Delta may be categorized as Farmland, Wetland, and Coast (Song et al., 2012). An elaborate irrigation system has been installed on the Yellow River Delta floodplain for better use of precious water resources. The system captured much of the water, sediment and nutrients, which resulted in strongly reduced water and sediment transport to the ocean (Huang et al., 2012). Increasing use of fertilizers on the irrigated farmlands likely impacted underlying aquifers of the Yellow River Delta (Chen et al., 2007, 2005; Bai et al., 2012). The wetland components of river deltas are some of the most productive ecosystems in the world, helping to water storage, flood mitigation and load of some pollutants and nutrients flowing through the inland into sea (Ladouche and Weng, 2005; Cui et al., 2012; Hunt et al., 1998; Jolly et al., 2008). Slight shifts in delta function can have strong impacts, not only on the wetlands, but also in large areas of the enclosing catchment (Négrel et al., 2003). Water diversion from the Yellow River began in July 2008, when wetlands A and B

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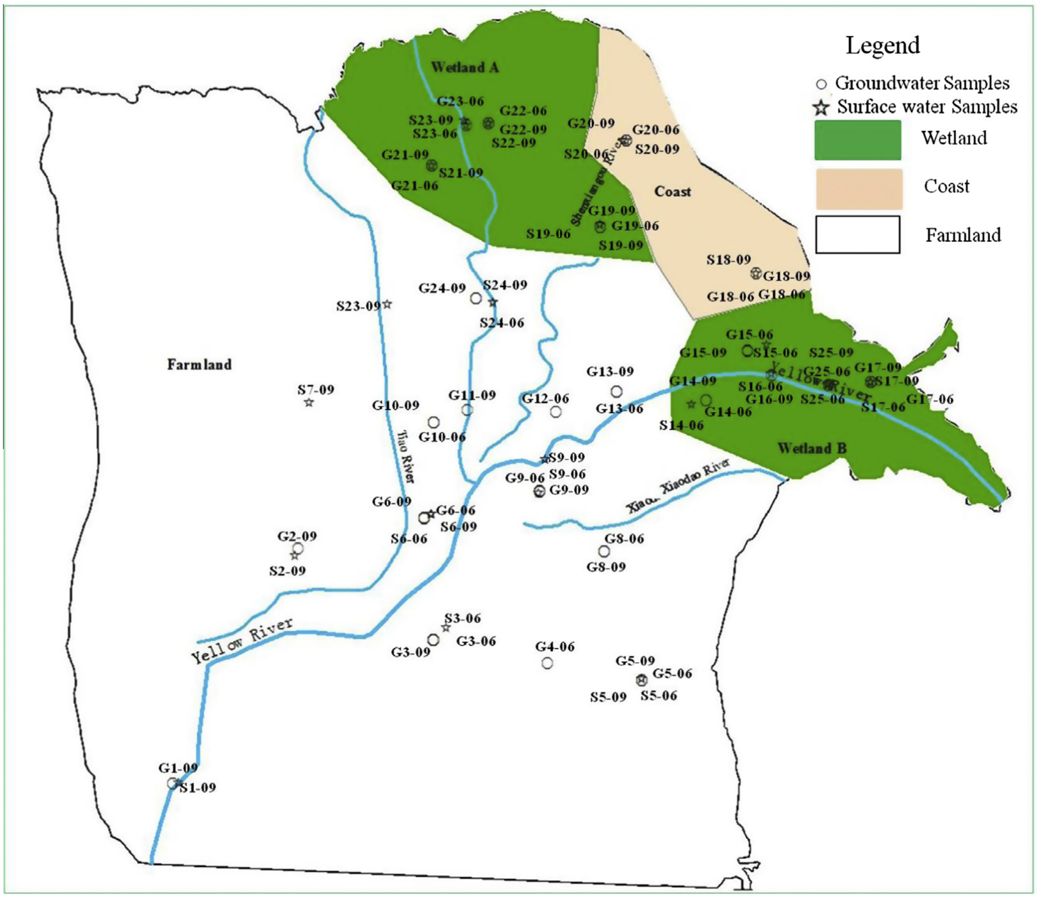

Fig. 1. Study area and relevant sampling locations for the both companies, i.e. abbreviation G3-06 means groundwater labeled 3 was sampled in the 6, 2011, whereas S3-06 means surface water labeled 3 was sampled in the 6, 2011.

(Fig. 1) were artificially filled in order to maintain a high surface water level. However, changes in river management protocols may lead to modifications in groundwater flow regimes, particularly when groundwater contains more salt than surface water. In these circumstances, changes in management procedure may lead to the mobilization of stored salts, resulting in increased salinization of wetlands (Jolly et al., 2008; Ghassemi et al., 1995). The Yellow River Coast region (Fig. 1) is being subjected to extensive oil and gas exploitation (Song et al., 2012), which activated seawater intrusion because a small drawdown of the groundwater head may cause a significant shift in the seawater-freshwater interface (Lim et al., 2013).

A study of hydraulic connection mechanisms between surface water and groundwater (GW–SW) is vital for sustainable use of the delta. Surface water and groundwater interact across a diversity of physiographic landscapes and climate regimes (Winter et al., 1999; Sophocleous, 2002; Winter, 2001). Most GW–SW research on deltas located in arid/semi-arid areas has focused on issues such as pollution, drainage and hydrological regime, including surface water impoundment and diversion. Deltas are prone to salinization caused by anthropogenic changes in hydrological cycles (Jolly et al., 2008). However, there is only a limited literature on these topics for the Yellow River Delta system.

Here, we report a GW–SW study of the impacts of ecological water diversion in the Yellow River Delta. Our specific objectives were to (1) synthesize information on hydrological and physicochemical parameters for evaluation of seasonal and spatial variations in the chemistries of surface water and groundwater affected by water diversion, (2) describe the relationships between surface water and groundwater, and quantify the contribution of the Yellow River to end users, and (3) identify hydrochemical facies that incorporate the dynamics of coastal groundwater freshening.

2. Methods and materials

2.1. Regional descriptions and site selection

The Yellow River Delta covers an area of 5400 km^2 (He et al. 1999), between latitudes 37°26′N and 38°10′N and between longitudes 118°21′E and 119°20′E (Fig. 1). In the modern era, a shift in the Yellow River created a new alluvial fan over an area of approximately 2200 km^2 (Gao et al., 1989). Quaternary delta sediment is approximately 300–500 m deep; there are aquifers with marine or terrestrial layers. The monsoon climate brings rainfall to the delta mainly concentrated in summer (June–September), with the annual average rainfall is approximately 594 mm. The mean annual potential evaporation is 2049 mm yr^{-1}, which far exceeds rainfall for the area.

Study sites were selected across three representative ecosystems regions in the Yellow River Delta. The farmland in the upper reach of the Yellow River is a default floodplain dominated by fluvial input from the Yellow River. Downstream from the Yellow River to the southeast and to the north are the wetlands, which are among the largest in Asia. Human impact is minimal in these wetlands. East of the delta, the coast comprises a saline foreshore, which is vulnerable to typhoon-driven storm surges. We investigated the surface water and groundwater of 68 sites distributed among three ecosystems to determine the impact of water diversion on spatial and seasonal variability in measured parameters.