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Chemical and isotopic constraints on evolution of groundwater salinization in the coastal plain aquifer of Laizhou Bay, China

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SUMMARY

A hydrochemical-isotopic investigation of the Laizhou Bay Quaternary aquifer in north China provides new insights into the hydrodynamic and geochemical relationships between freshwater, seawater and brine at different depths in coastal sediments. Saltwater intrusion mainly occurs due to two cones of depression caused by concentrated exploitation of fresh groundwater in the south, and brine water for salt production in the north. Groundwater is characterized by hydrochemical zonation of water types (ranging from Ca–HCO_3 to Na–Cl) from south to north, controlled by migration and mixing of saline water bodies with the regional groundwater. The strong adherence of the majority of ion/Cl ratios to mixing lines between freshwater and saline water end-members (brine or seawater) indicates the importance of mixing under natural and/or anthropogenic influences. Examination of the groundwater stable isotope $\delta^{18}O$ and $\delta^{2}H$ values (between −9.5‰ and −3.0‰ and −75‰ and −40‰, respectively) and chloride contents (~2 to 1000 meq/L) of the groundwater indicate that the saline end-member is brine rather than seawater, and most groundwater samples plot on mixing trajectories between fresh groundwater ($\delta^{18}O$ of between −6.0‰ and −9.0‰; Cl < 5 meq/L) and sampled brines ($\delta^{18}O$ of approximately −3.0‰ and Cl > 1000 meq/L). Locally elevated Na/Cl ratios likely result from ion exchange in areas of long-term freshening. The brines, with radiocarbon activities of ~30 to 60 pMC likely formed during the Holocene as a result of the sequence of transgression-regression and evaporation; while deep, fresh groundwater with depleted stable isotopic values ($\delta^{18}O$ = −9.7‰ and $\delta^{2}H$ = −71‰) and low radiocarbon activity (<20 pMC) was probably recharged during a cooler period in the late Pleistocene, as is common throughout northern China. An increase in the salinity and tritium concentration in some shallow groundwater sampled in the 1990s and re-sampled here indicates that intensive brine extraction has locally resulted in rapid mixing of young, fresh groundwater and saline brine. The $\delta^{18}O$ and $\delta^{2}H$ values of brines (~−3.0‰ and −35‰) are much lower than that of modern seawater, which could be explained by 1) mixing of original ($\delta^{18}O$ enriched) brine that was more saline than presently observed, with fresh groundwater recharged by precipitation and/or 2) dilution of the palaeo-seawater with continental runoff prior to and/or during brine formation. The first mechanism is supported by relatively high Br/Cl molar ratios (1.7×10^{-3}–2.5×10^{-3}) in brine water compared with ~1.5×10^{-3} in seawater, which could indicate that the brines originally reached halite saturation and were subsequently diluted with fresher groundwater over the long-term. Decreasing ^{14}C activities with increasing sampling depth and increasing proximity to the coastline indicate that the south coastal aquifer in Laizhou Bay is dominated by regional lateral flow, on millennial timescales.

1. Introduction

Currently about 44 percent of the world's population lives within 150 km of the coast (UN Atlas, 2010). Along much of China's 18,000 km of continental coastline, population densities average between 580 and 1945 per square kilometer, and of China's 1.3 billion people, over 60% live in 14 coastal provinces (Shi, 2012). The rate of population growth in coastal areas is accelerating and increasing water resources demand and economic development adds to pressure on the environment.

Seawater intrusion is a widespread geologic hazard in many coastal regions around the world. It generally occurs when withdrawal of fresh groundwater from coastal aquifers results in declining groundwater levels, facilitating lateral and/or vertical

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migration of saline water, causing deterioration of groundwater quality (Barker et al., 1998; Barlow and Reichard, 2010). Salinization of coastal aquifers can occur due to simple, direct seawater intrusion, but it can also involve a range of complex geochemical processes which control water quality in different ways; e.g., inter-aquifer mixing, mobilization of brines, water–rock interaction and anthropogenic contamination (Vengosh et al., 2005). Rising sea levels, and increasing climate variability (e.g. longer droughts) are likely to place increasing pressure on coastal aquifers both in northern China and globally in coming years (Werner and Simmons, 2009; Green et al., 2011). In this context, a rigorous understanding of the physical and chemical processes involved in salinization of coastal aquifers is vital for the future management of these vulnerable water resources.

The Bohai Sea Coast is the region most seriously affected by seawater intrusion in China, particularly Laizhou Bay in northern Shandong province (Fig. 1). The problem has resulted due to intensive groundwater extraction during rapid development in the region since the 1970s, and has been recognized by local authorities since 1976 (Ji, 1991). The coastal aquifers of Laizhou Bay have recently been the focus of attention due to increasing stress on fresh water resources and environmental degradation. Management of fresh groundwater resources in coastal aquifers requires an understanding of the processes controlling groundwater geochemical evolution and flow system dynamics. By examining hydrochemical and isotopic data together with geology, topography and hydrogeological data, seawater intrusion can be comprehensively assessed as a geologic hazard (e.g. Vengosh et al., 2005; Andersen et al., 2005; Jorgensen et al., 2008). The approach of using multiple sources of data can improve understanding of hydrogeologic processes and aid the reliability of groundwater flow models (e.g. Vengosh et al., 2002; Carrera et al., 2005). However, comprehensive approaches to groundwater problems involving use of chemistry and isotopic indicators are few in coastal aquifer research in China.

The objectives of the present paper are to provide an understanding of the evolution of groundwater in the south coastal plain of Laizhou Bay in relation to recharge, salinity sources, mixing behavior and palaeo-evolution of groundwater by considering a wide selection of geochemical indicators. The data examined includes field observations of water table fluctuations and analysis of hydrochemical and stable isotopic compositions of groundwater. It is likely that much of the water being exploited was recharged under different climatic conditions to the present day (e.g. Chen et al., 2003; Kreuzer et al., 2009) and that the distribution of salinity has resulted from a combination of past and recent processes, including a number of phases of regression, transgression, brine formation and mixing. The results have significant implications for the management of the exploitation and recharge of coastal aquifers that are intensively exploited globally, and demonstrate the value of using isotopic indicators in conjunction with other hydrogeological information.

2. Site description

2.1. Background of study area

The study area is the southern coastal area of Laizhou Bay, including the 43 km-long coastline and adjacent area of approximately 1400 km^2 (Fig. 1). Elevation of the coastal plain ranges from 30 m a.s.l. in the south to 1–2 m a.s.l. in the north (Chen et al.,1997) with an average slope of 0.5‰ towards the sea. The Wei River, Yu River and Jiaolai River flow through the study area into Laizhou Bay. The area belongs to a sub-humid monsoon climate, with mean air temperature of 11.9 °C. The annual mean precipitation is 660 mm, generally concentrated in June, July and August. Average annual potential evapotranspiration is approximately 1400 mm. Past work in this region has been carried out examining the mechanism, development, and preventative countermeasures for seawater intrusion (e.g. Zhang and Peng, 1998; Xue et al., 2000), and the formation of preferential channels of salt water intrusion (e.g. Zhang et al., 1996; Li et al., 2000).

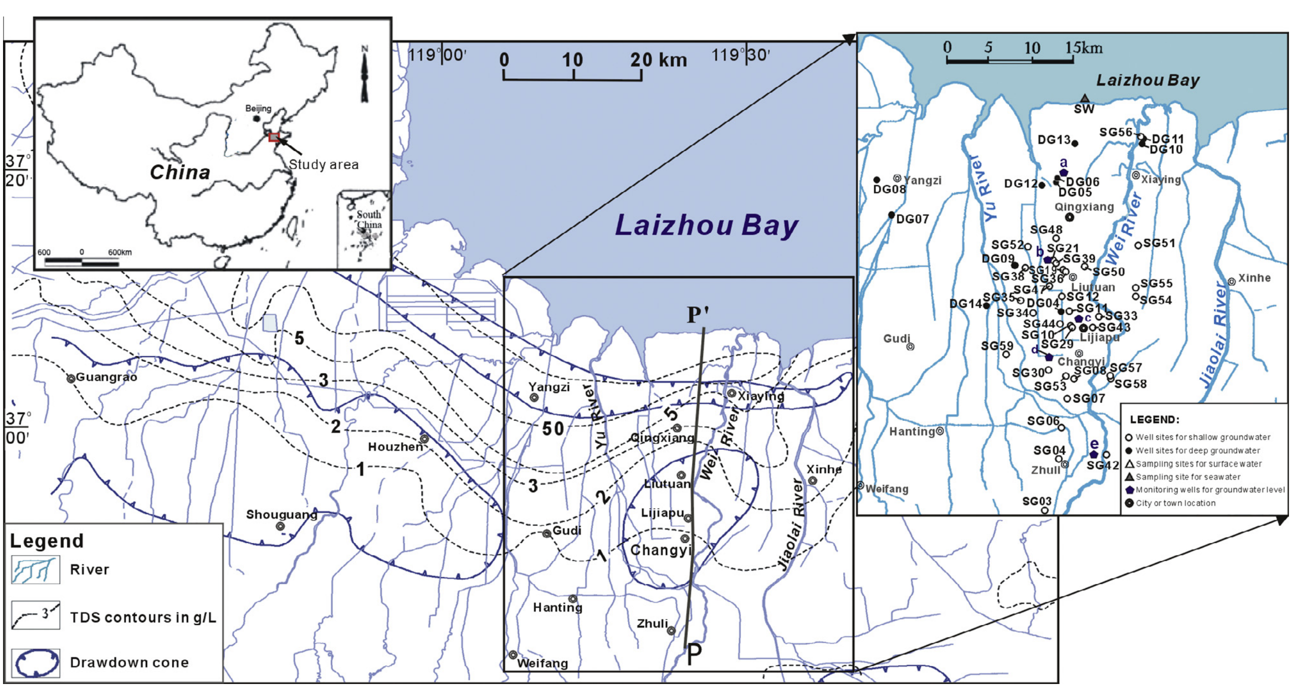

Fig. 1. Location map of the study area, modified after TJR (2006). TDS concentrations were measured in November 2005. Drawdown cone refers to area enclosed by 0 m water table height contour. P–P′ line is the location of the cross-section in Fig. 2. Right-upper map for showing the sampling wells in the study area.