Estuarine, Coastal and Shelf Science 181 (2016) 51–60

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Responses of submarine groundwater to silty-sand coast reclamation: A case study in south of Laizhou Bay, China

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A R T I C L E I N F O

Article history:
Received 18 February 2016
Received in revised form
13 July 2016
Accepted 12 August 2016
Available online 15 August 2016

Keywords:
Submarine groundwater
Reclamation
Laizhou Bay
Silty coast
Electrical conductivity

A B S T R A C T

Coastal reclamation can result in considerable changes in the quality and quantity of submarine groundwater at the land/sea interface. In this study, submarine groundwater monitoring wells and water samples were designed and implemented to get data of groundwater level, electrical conductivity, temperature, and hydrochemistry data to examine the responses of silty-sand submarine groundwater in different sedimentary strata to reclamation in south of Laizhou Bay. The submarine groundwater is mainly saline water and its salinity in the deep aquifer is higher than that of seawater and close to brine. It was formed in the Late Pleistocene and Holocene. Drilling core data indicates that there is a stratigraphic boundary at a depth of 18.58 m, with Holocene strata above, and Late Pleistocene strata below, this level. Continuous electrical conductivity data indicates that the submarine groundwater properties are stratigraphically distributed in this study area. And there is an interface at a depth of 38 m. Above the 38 m depth, the water quantity of submarine ground-saline water is freshening. The major ions showed a tendency to change continually above 25 m, but the tended to stabilize below 25 m depth. Freshwater is the major recharge source in the upper section of the Holocene strata, between the surface and 8.00 m depth, and the hydrochemical type has changed from Cl–Na to Cl·HCO_3–Na. In the lower section of Holocene strata (8.00–23.00 m) and upper section of late Late Pleistocene strata (23.00–38.00 m), groundwater is influenced by seawater and groundwater of upper aquifer. The freshwater, seawater, and groundwater recharge in the upper aquifer has no influence on the groundwater in the section below the late Late Pleistocene (between 38.00 and 49.15 m) and the early Late Pleistocene strata (between 49.15 and 75.00 m). The filling layer, added in the coastal reclamation project, is comprised of clayey silt and fine sand, and its high porosity means that it is suitable for water storage. After the reclamation, meteoric water was stored in the filling layer that became the stable recharge resource. The recharge resource and the filling layer can improve the properties of the confined aquifer to increase the groundwater level. They may also influence the groundwater quantity and the flow direction. The groundwater in the Holocene strata is clearly influenced by recharge and the previously saline water aquifers receive freshwater on an on-going basis, such that the water is now becoming fresh.

1. Introduction

Shallow marine hydrogeological systems are found at the boundary between the land and the sea, and submarine groundwater stored in these systems has close hydraulic connections with terrestrial groundwater and seawater. These systems are also situated in what is known as the critical zone, and have been the focus of recent global research (Yang and Zhang, 2014; National Research Council, 2012). Recently, many reclamation projects have been builded in coastal area those environment has been changed. Because of coastal reclamation, the original shallow sea hydrogeological systems gradually have been changed to terrestrial

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http://dx.doi.org/10.1016/j.ecss.2016.08.012
0272-7714/

hydrogeological systems. In this slow and subtle process, the physical and chemical characteristics of the original submarine groundwater will be changed (Hu and Jiao, 2014). It has leaded to a series of important environmental hidden dangers in coastal area.

Previously, a research team from the Department of Earth Sciences at the University of Hong Kong used numerical methods (Depuit assumption, Ghyben-Herzberg assumption, and transient flow analysis) and groundwater simulation model (FEFLOW, PHREEQC2.0) to examine changes in groundwater flow, groundwater level, salt water–freshwater interface and the freshening time attributable to coastal reclamation. They found that reclamation improved the groundwater level and caused the saline water–freshwater interface to move towards the marine environment. They also found that there was a relationship between the freshening time and the groundwater flow velocity in Tseung Kwan, Hong Kong, and on the Shekou Peninsula, Shenzhen (Jiao et al., 2006; Guo and Jiao, 2007; Chen and Jiao, 2007, 2008; Hu and Jiao, 2010, Hu and Jiao, 2014; Chen and Jiao, 2013). Kim et al. (2006) and Salem et al. (2015) also used hydrogeochemical analysis to explore the effects of coastal reclamation on the quantity of groundwater and the mixing processes between pre-reclamation groundwater and freshwater that infiltrated into reclaimed coastal areas. Most research was focused on sand coast where the groundwater is fresh water or sea water which is from seawater intrusion.

Different from past research, this study is focused on silty-sand submarine ground-saline water (the salinity higher than sea water) in a silty-muddy coast. The submarine ground-saline water was formed from Late Pleistocene to Holocene. Based on field data, there is a targeted design of monitoring wells, monitoring programs and water samples. Groundwater level, groundwater electrical conductivity (EC), and hydrochemistry data are used to examine the responses of submarine groundwater in different sedimentary strata (early Late Pleistocene strata, late Late Pleistocene strata and Holocene strata) to reclamation.

2. Background of study area

2.1. Geological and hydrogeological settings

The study area is located in the southern part of Laizhou Bay, Bohai Sea, China (37°08′35″–37°17′15″ N, 119°08′10″–119°15′45″ E) (Fig. 1A and B and 2). The southern part of Laizhou Bay belongs to the coastal marine plain and fluvial delta depositional system of the Late Pleistocene. The main deposition layers in the study area are composed of Quaternary sediments that range from 30 to 50 m thickness in the south to 400 m thickness in the north (Leng et al., 2009; Xue et al., 2000). This is one of the most important brine storage areas in the coast of China. The quality of the groundwater varies greatly, and can be described as shallow fresh groundwater, brackish groundwater, saline groundwater, brine. Some saline groundwater and brine aquifers extend to the submarine groundwater aquifers. The salinity of the groundwater presents “low-high-low” distributing character from north to south and from shallow to deep aquifers. The shallow freshwater aquifer is mainly comprised of fine sand and medium fine sand. Hydrochemical types of it are $Cl\cdot HCO_3\cdot SO_4$–$Ca\cdot Na$, Cl–$Ca\cdot Na$, HCO_3–$Ca\cdot Na$, and $HCO_3\cdot SO_4\cdot Cl$–Na (Bi et al., 2012) and the value of total dissolved solids (TDS) is less than 1 g/L. Aquifers of brackish water, saline water, and brine are distributed below the fresh groundwater; these aquifers are mainly comprised of silty sand and the TDS concentration range from 1 to 200 g/L. The hydrochemical types are mainly Cl–$Na\cdot Ca$, Cl–$Na\cdot Mg$, $Cl\cdot SO_4$–Na, and Cl–Na (Bi et al., 2012). In the south of the study area, some groundwater depression cones are formed by over-exploitation of the groundwater. The exploiting depth is up to 50 m in some brine areas. The intensive exploitation has resulted in the formation of depression cones, because of which the groundwater now flows from the piedmont and marine area to the middle plain area.

Before the coastal reclamation, the study area was in the silty-muddy coastal tidal flat, and the submarine groundwater belonged to the shallow sea hydrogeological system. Submarine groundwater was saline water which was formed from Late Pleistocene and the hydrochemical type was Cl–Na. Seawater was the main source of recharge, and the groundwater flowed towards the land because of the groundwater depression zones created by the intensive brine exploitation. After the reclamation, an artificial coastal line was created and the study area was covered with a layer of clayey silt and fine sand from sediment of Laizhou Bay. The filling layer was about 5.0 and 7.0 m thickness and extended to 30.43 km^2 (Ma et al., 2014). Meteoric water became the main recharge resource and groundwater flow pathway was increased.

2.2. Climatic and hydrological background

The study area is the warm temperate zone half moist monsoon climatic region. The mean annual temperature is 53.9 °F, and the average annual precipitation is 731 mm. Precipitation is the main fresh water resource in the study area. Of the total annual precipitation, 70–80% falls between July and September. The mean annual evaporation capacity is 1648.1 mm and 50% of evaporation capacity occupied largely from March to June. Bailang River is the main river in study area with annual average runoff $3.8 \times 10^7 m^3/a$ (Bi et al., 2012; Gao et al., 2015; Han et al., 2014).

2.3. Strata

Several transgression layers and saline-water sedimentations formed in the Early and Middle Pleistocene. Since the Late Pleistocene, the study area has experienced many glacial–interglacial climatic alternations. There have been three obvious temperature fluctuations, namely from 85 to 76 ka BP, 50 to 24 ka BP, and 10 to 4 ka BP (Gao et al., 2015). These three periods were accompanied by three transgressions (named of Cangzhou transgression, Xianxian transgression, Huanghua transgression), known as the marine–continental transition depositional environment (Fig. 1A). The two cold dry periods (Early Dali ice period and the Late Dali ice period) were from 76 to 50 ka BP, and from 24 to 10 ka BP, when there was a continental sedimentary environment (Zhang et al., 2005). The marine–continental transition sedimentary strata formed as a result of transgression and regression. From top to bottom, the sedimentary layers are as follows: the Late Holocene continental layer, the Holocene Huanghua transgression layer, the Early Holocene continental layer, the Late Pleistocene glacial continental layer, the Xianxian transgression layer from the later part of the Late Pleistocene, the continental layer from the later part of the Late Pleistocene and Early glacial age, and the Cangzhou transgression layer from the early part of the Late Pleistocene (Qin et al., 1985).

Accelerator mass spectrometry radiocarbon dating ($AMS^{14}C$), optically stimulated luminescence (OSL), particle size data, micropaleontology, and the lithological description were used to divide the shallow strata into five sedimentary units:

(1) The Holocene marine deposits are from 5.8 to 18.58 m depth.
(2) The late Late Pleistocene land formation is from 18.58 to 23.27 m depth.
(3) The Xianxian transgression layer of the later part of the Late Pleistocene is from 23.27 to 49.15 m depth,