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ORIGINAL ARTICLE

Seawater intrusion and coastal aquifer management in China: a review

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Abstract Seawater intrusion has been an important topic in hydrogeology in China in recent decades. The rapid growth of the population and economy in the coastal regions has been consuming a tremendous amount of groundwater resources and has increased the extent of seawater intrusion. The spatial discrepancy of water resource distribution has caused the studies of seawater intrusion into China to mainly be concentrated on the area around the Bohai Sea in the northern part of China. The total area of seawater-intruded land due to excessive groundwater utilization in the area was estimated to be approximately 2,457 km^2 in 2003. Great efforts have been made to mitigate the extent of seawater intrusion and to secure more freshwater resources, including building monitoring networks, subsurface barrier and groundwater reservoirs, and artificial infiltration facilities. Management projects over the years were evaluated to satisfy the objectives and to provide valuable experiences for future research and planning. It is expected that the coastal groundwater conditions of the northern region will improve through the development of a national water resource plan, such as the ongoing south-to-north water diversion project.

Keywords Coastal groundwater resource in China · Seawater intrusion · Subsurface barrier · Groundwater reservoir · Artificial infiltration

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Introduction

Groundwater in China is a vital resource for sustaining the community and economy. In the coastal provinces of China, the amount of groundwater utilization reached 4.4×10^{10} m^3 in 2009 (Ministry of Water Resources of China 2010). As groundwater use in coastal areas has increased, both the quality and quantity of groundwater resources have deteriorated because of excessive development and improper management. The critical issues are groundwater table decline, and seawater intrusion resulting in well depletion or the contamination of groundwater with seawater.

Seawater intrusion is a natural phenomenon driven by the density difference between freshwater and seawater, but the extent of intrusion has been largely aggravated by the extraction of groundwater. The study of seawater intrusion has a long history. The latest review studies have been documented in North America (Barlow and Reichard 2010; Bear et al. 1999), Australia (Werner 2010), Europe (Custodio 2010), South America (Bocanegra et al. 2010), Africa (Steyl and Dennis 2010) and the island countries of the Pacific Ocean (White and Falkland 2010). In Asia, China has an 18-thousand-km coastline (Fig. 1). In China, much work has been done in recent decades regarding seawater intrusion, including the theoretical studies, analytical/numerical studies, laboratory and field experiments, and engineering projects. However, there is a lack of an overview of seawater intrusion in China, though the topic has been of interest for overseas scholars (Post and Abarca 2010). One of the difficulties of knowing the state of seawater intrusion in China is that most of the related publications and important data are mainly available in Chinese.

The primary aims of this paper were the following: to provide a summary on groundwater resources along coastal

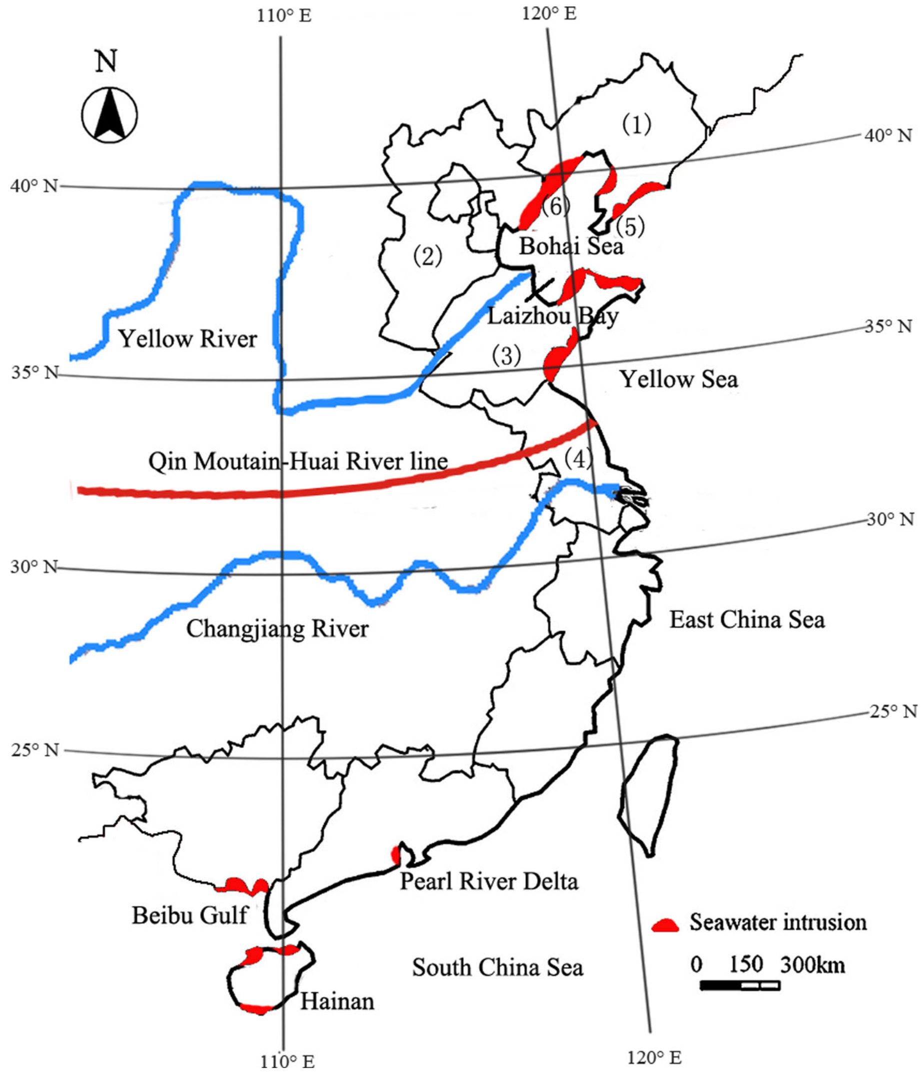

Fig. 1 Sketch map of the extent of seawater intrusion in China

regions of China; to describe the extent of seawater intrusion in coastal areas of China; and to introduce the engineering projects for mitigating seawater intrusion and securing groundwater resources around the Bohai Sea. This paper also discusses the challenges and prospects of China's coastal groundwater management.

Coastal groundwater resources in China

Several rounds of national hydrogeological surveys have been conducted in China since the 1950s, with the latest completed in 2002. It was reported that the annual ground water recharge amounts to 8.7×10^{11} m^3, of which 2.9×10^{11} m^3 is exploitable (Jiao and Wen 2004). However, the distribution of groundwater is highly imbalanced between the northern and southern parts, which are separated by a geographical boundary called the Qin Mountains–Huai River Line. The water resource per capita for the northern coastal provinces such as Hebei and Shandong is even lower than that in the middle-eastern countries (FAO 2003; Ministry of Water Resources of China 2010).

The use of groundwater for irrigation, industrial, and domestic purposes has been increasing in the coastal regions. A report claimed that nearly 40 % of the world's population lives within 100 km of a coastline, an area that accounts for only 22 % of the world's land mass (Rosen 2000). Approximately, 37 % of China's total population and approximately, 65 % of its total GDP belongs to the coastal provinces (National Bureau of Statistics of China 2011). The annual extracted groundwater increased from 6.19×10^{10} m^3 in 1980 to 1.069×10^{11} m^3 in 2000 (Jiao and Wen 2004). The groundwater demand has increased in both the northern and southern parts, but the groundwater scarcity is more serious in the north.

In the coastal area, the ratios of extracted groundwater to potential groundwater resource in the northern provinces are much higher than in the southern provinces (Zhang and

Li 2004). Excessive groundwater pumping has caused a remarkable drawdown of groundwater levels in the North China Plain, generating a regional cone of depression in an area of over 2,000 km^2 in the coastal Hebei Province alone (Jiao and Wen 2004). Therefore, excessive pumping is common in the northern coastal provinces and has led to severe seawater intrusion. High-salinity water is usually unfit for irrigation, industry, and drinking.

Extent of seawater intrusion in China

The extent of seawater intrusion is mainly determined by three conditions: (1) the groundwater recharge rate from meteoric water, which depends on the climate and geographic conditions; (2) the permeability of the hydrogeological system; and (3) the groundwater extraction rate. Many Chinese scholars have conducted studies on the seawater intrusion issue in China since the 1990s (Li and Chen 1996; Cheng and Chen 2001; Xue et al. 1993; Wu et al. 1993). The extent of seawater intrusion around the Bohai Sea area of North China is much more serious than in the other areas, in accordance with the status of excessive groundwater use in the area. In South China, the seawater intrusion problems have been mostly investigated in Pearl River Delta area, coastal area in Beibu Gulf, and Hainan. The seawater intrusion areas in this study are represented in Fig. 1, and it is noted that the scale of intrusion area is just for demonstration.

North China

Seawater intrusion in North China mostly occurred in the area around the Bohai Sea, which has become one of the fastest-developing areas in China. There are several large ports and cities along the Bohai Sea's coastline, and the population density is high. The climate is influenced by monsoons, and the rainfall is much less than in the south. The groundwater systems around the Bohai Sea were mainly formed by Quaternary sediments and fractured rock (Liu et al. 2004). The permeable layers consist of coarse-to-fine sand from fluvial sediments and are usually separated by several marine confining layers. Seawater more easily intrudes into the highly permeable aquifers and excessive extraction causes large groundwater drawdown to aggravate the intruded extent. Moreover, seawater often flows inland through the river channel for tens of kilometers and then intrudes into the aquifer through the riverbed.

The total seawater-intruded area (salinity >1,000 mg/L) around the Bohai Sea in 2003 was 2,457 km^2 and increased by 937 km^2 over the 1980s (Wen et al. 2007). The seawater intrusion in this area resulted in drinking water problems for more than 400,000 people, and more than 8,000 irrigation pumping wells were abandoned. The seawater intrusion modes in the area are classified as modern and paleo-seawater intrusion.

Modern seawater intrusion

In the southern land surrounding the Laizhou Bay in Shandong Province, the salinities of numerous groundwater samples were measured to be greater than 1,000 mg/L up to tens of kilometers inland from the coastline (Han et al. 2011). The intruded area was estimated to be more than 700 km^2 (Sun et al. 2006). The in situ hydraulic conductivity tests in the region indicated good permeability of the aquifer system, consisting of coarse and fine silty sand (Xue et al. 2000; Wu et al. 1993).

In Dalian, a large port city, seawater intrusion was recognized as early as the 1960s. The intruded area was reported to be 468 km^2 in 2002 (Sun et al. 2006). The common aquifer system in the area consists of carbonate rocks, and seawater easily enters the system through the conduits and fractures. In another port city, Qinhuangdao, the intruded area was estimated to be 342 km^2, and the maximum intruded distance was up to 12.5 km (Yang et al. 2008).

Paleo-seawater intrusion

In the coastal land around the southern part of Laizhou Bay, high-salinity brackish and brine water was found in a large scale (Zhang and Peng 1998). The salinity of the brine water was even as high as 1.446×10^5 mg/L (Han et al. 2011). It was assumed that the high-salinity water originated from paleo-seawater and was affected by the evaporation process (Xue et al. 2000). The occurrence of paleo-seawater intrusion in the area was related to the sea-level fluctuation and the geologic processes during the Quaternary. During the period of 70–39 thousand years before present, with the sea level descending, the Bohai Sea became an enormous closed salt lake. The pore water in the vadose zone also encountered strong evaporation, resulting in the high-salinity brine water. There have been three cycles of marine transgression and regression since the Late Pleistocene period. The lowest sea level in the Bohai Sea was approximately 160 m below the current mean sea level between 20,000 and 15,000 years before present, after which it rapidly rose to the current level, with some fluctuations (Zhao et al. 1982). The less-permeable layers were formed by marine sediments at the highstand of the sea level. Meanwhile, seawater was retained in the pores of sediments. When the sea level descended during the glacial periods, part of the seawater in the pores was flushed out. Some of the seawater, however, especially in the deep system, was retained in the system due to the inhomogeneity and low permeability of the geologic formations. A similar paleo-seawater intrusion process has been found in other coastal aquifers (Kooi et al. 2000).

Laboratory chemical analyses of groundwater samples to determine the origin of the high-salinity brine water in the area of southern Laizhou Bay (Han et al. 2011) revealed that the age of the high-salinity water is as high as 21,700 years according carbon isotopic dating. The relative proportions of Na, Ma, Cl, and SO_4^{2-} were similar to the contents in the seawater, which indicates that the saltwater in that region originated from paleo-seawater. The relation of δ^2H and $\delta^{18}O$ in the water samples reflects the increasing influence of evaporation as a major process of salinity production.

South China

In the coastal area of south China, the study of seawater intrusion is limited because of the abundant surface water resources and the small ratio of groundwater use. In the coastal areas of Beibu Gulf and Hainan, seawater intrusion was found at the observation sites (Xun et al. 2007; Zhou et al. 2003; Yao et al. 2011).

In the Pearl River Delta, however, surface water quality has been deteriorating due to pollution as a result of the rapid growth of industry, particularly since the 1980s (Lu et al. 2009). Groundwater is becoming an important water resource in the area. Seawater, influenced by tides, intruded into the surface water system in the Pearl River estuary (Chen et al. 2009) and then contaminated the groundwater in the underlying aquifer system. A survey of groundwater salinity from the shallow wells around the Pearl River estuary indicated the salinities for most samples were less than 600 mg/L, while in some cases the salinity was more than 5,000 mg/L during the low water levels in winter (Sun et al. 2011).

When we looked into the deeper system, high-salinity groundwater could be found at a large scale. Recently, (Wang and Jiao 2012) analyzed the water samples from 40 deep wells drilled in the basal aquifer in the Pearl River Delta. A large area of high salinity was defined, and the maximum seawater-intruded area (salinity >1,000 mg/l) extends approximately 75 km inland from the sea. ^{14}C dating suggested that the mixed saltwater in the confined basal aquifer originated from paleo-seawater during the Holocene transgression.

Given the above, seawater intrusion has seriously threatened the groundwater in the coastal areas of China and has caused considerable economic losses and environmental problems (Liu 2004; Xu et al. 2009; Han 2003). Proper management is required to mitigate the seawater intrusion problem.

Management of China's seawater intrusion problem

The management of coastal groundwater has a history of a few decades around the world (Todd and Mays 1980). The key issue in management is to choose a suitable plan according to the local hydrogeological conditions and climate. Poor management could harm the precious freshwater resources, but good management should lead to the sustainability of these resources. In addition to the scarcity of rainfall in northern China, a higher level of groundwater management is required due to the rapid growth of the economy and the population (Jiang 2009) and the associated increase in water demands.

In China, the management of groundwater resources is mainly run by the government and the institutes funded by the government. Therefore, the efficiency of management is determined by government policies and funds. The Chinese government has realized the importance of groundwater protection, especially when the coastal provinces play the large role in the national economy. In this section, the status of groundwater monitoring networks, artificial recharge projects, and groundwater reservoirs are introduced. These projects are mostly distributed in the area around the Bohai Sea.

Monitoring network

To understand the extent of the seawater intrusion problem and its impact on the utilization of groundwater resources, a more elaborate groundwater monitoring network is necessary. The modern groundwater quality monitoring network must satisfy the objectives of spatial coverage, cost, ease of maintenance, and other factors (Loaiciga et al. 1992). A three-dimensional seawater intrusion observation network was built in Longkou city in 1989 (Xue et al. 1993; Wu et al. 1993), where 31 monitoring wells are densely distributed in an 8,000-m^2 area. In recent years, many new monitoring systems around the Bohai Sea have been installed using specially drilled wells, existing pumping wells, and wells abandoned due to seawater intrusion, which could not be used as production wells but could be used as monitoring wells. The monitoring network in China reported by (He and Li 2006) had more than 23,800 monitoring wells in an area of nearly a million km^2, which covered many coastal areas. The central government of China plans to establish a national groundwater observation network including tens of thousands of wells with a budget of approximately 1.8×10^9 yuan (Qiu 2010).

When an agency regulates groundwater management facilities, a reliable and feasible plan is required. The plan should consider key factors, including recharge, groundwater flow, function of the engineering project, and so on. A GIS-based digital regulating system that provides

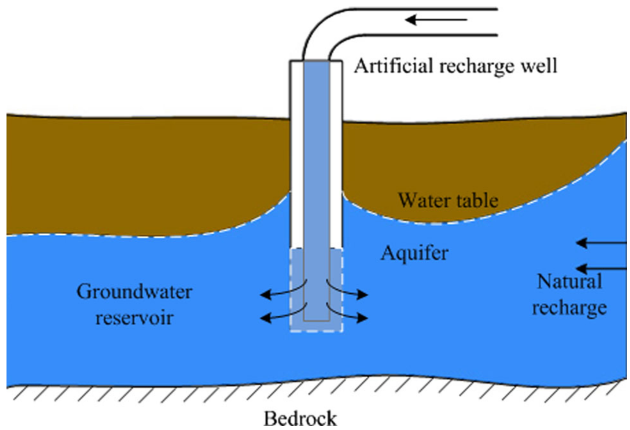

Fig. 2 Sketch map of the concept of artificial recharge

calculation tools and visualization capabilities for pre- and post-processing for a study area is an efficient solution for decision-makers (Dawoud et al. 2005). In China, such a system has been implemented in some coastal areas for groundwater management. For example, a digital water resource management system was developed for Longkou city to link information on rainfall, groundwater level, and water storage of surface and subsurface reservoirs. This system can help provide decision-makers with management scenarios (Ma 2005).

Aquifer artificial recharge

The artificial recharge of groundwater is a short- or long-term method to recover the groundwater level and prevent seawater intrusion. The surface water is recharged into the aquifer through trenches, wells, or other facilities where the surface water infiltrates into the soil and moves downward (Bouwer 2002) (Fig. 2). In China, a field experiment was conducted to study the effect of artificial recharge (Ma 2005).

The government of Laizhou city has provided substantial financial support for projects controlling seawater intrusion. Two sluice gates were built to prevent seawater migrating toward upstream at the end of the 1970s on Wang River, which discharges to the Bohai Sea. Meanwhile, several conduits were built to transport the water from nearby reservoirs to the Wang River. Hundreds of infiltration trenches and wells have been built where water from the river can be infiltrated into the adjacent aquifers. The groundwater level was observed to increase after these facilities were constructed, especially during storm periods. It was reported from the observation data in the infiltration recharge area that the groundwater level rose to 3.17 m during the wet season in 1990, which was much more significant than without the artificial infiltration facilities (Ma 2005). The method of groundwater artificial recharge in China is usually applied in groundwater reservoir project.

Subsurface barrier and groundwater reservoir

Building subsurface barrier is a direct method for preventing seawater intrusion. The subsurface barrier is usually built using the high-pressure jet grouting method, which is a construction process in which a high-pressure jet of fluid is used to break up and loosen the soil at depth in a borehole and to mix it with a self-hardening grout to form a barrier under the ground. The efficiency of subsurface barrier has been discussed in experiments and numerical simulations (Luyun et al. 2011). In China, subsurface barrier is also used to form groundwater reservoir.

A groundwater reservoir in this study refers to aquifers with a subsurface barrier for collecting and storing water. Hydrogeological setting is a prerequisite for site selection to construct a groundwater reservoir (Osman and Abdullah 2013). The regional Quaternary aquifers in the area around the Bohai Sea consist of fluvial fans, alluvial fans, and lacustrine deposits. Generally, four Quaternary aquifer layers formed from the lower Pleistocene to the Holocene are distinguished in this region, based on the lithologic studies (Fig. 3) (Zhou et al. 2012). The groundwater reservoirs in the low plain around the Bohai Sea usually use the shallow aquifers (I and II), which were formed with fine sand to sandy gravel.

It was reported that eight groundwater reservoirs had been built in this region, with the total capacity of 2.89×10^8 m^3 (Sun et al. 2007). In this study, we listed five of them in the coastal areas of Shandong and Liaoning provinces (Fig. 4).

The groundwater reservoir in Longkou city was a major project for preventing seawater intrusion and storing freshwater. More than 7,000 guide holes have been drilled, and more than 32,000 tons of cement and 2,400 tons of clay have been consumed in jet grouting to build the subsurface barrier (Wu et al. 2008). The total length of the barrier was approximately 6,000 m, and the average height was approximately 27 m, including the part that was embedded into the bedrock, forming a closed underground water-blocking wall (Fig. 5). The groundwater reservoir behind the barrier, together with thousands of infiltration trenches and wells, had a storage capacity of approximately 5.4×10^7 m^3. This project took 3 years and cost approximately 4.25×10^7 yuan (1995) (Liu et al. 2003) and successfully fulfilled the objectives for preventing seawater intrusion and storing fresh groundwater resources for the local community in Longkou city.

Another example is the Wang River groundwater reservoirs in Laizhou, Shandong Province. The length of the subsurface barrier was 3,593 m. It was calculated that the

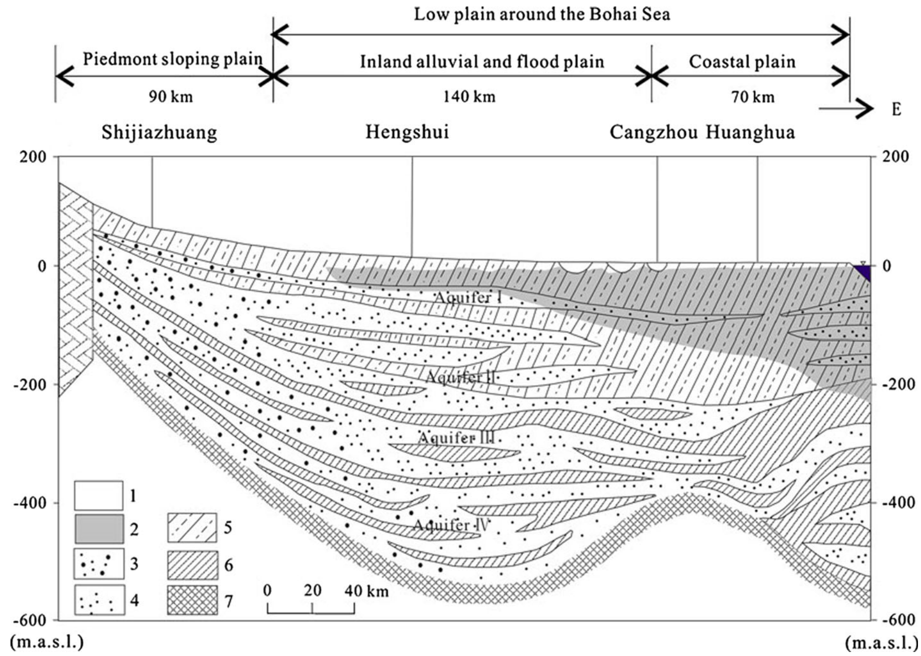

Fig. 3 Hydrogeological cross section in the low plain around the Bohai Sea (from Zhou et al. 2012). *1* Fresh water aquifers. *2* Saline and brackish water aquifers. *3* Sandy gravel. *4* Sand. *5* Silty clay. *6* Clay. *7* Tertiary formation

Fig. 4 Locations of the groundwater reservoir around the Bohai Sea

potential storage capacity was more than 5.6×10^7 m^3 (Li et al. 2006). A total of 1,312 infiltration wells and 187 trenches were constructed over the riverbed to provide speedy infiltration pathways. The average depth of the bored wells is 16 m. The bored wells penetrated the aquifers and terminated in the bedrock. The design capacity of the bored wells ranged from 150 to 499 m^3/day, depending on the depth of the wells and the aquifer properties. The bored wells were not backfilled, and they can be opened for maintenance if necessary. The infiltration capacity of a trench was measured to be approximately 217 m^3/day. The infiltration facilities produce an annual infiltration of 3.2×10^7 m^3 down to the aquifers. On average, the chloride concentration is reduced by 50 %. The groundwater satisfies the drinking water standard and has solved the water problems for residents and livestock in 10 villages. Every year, approximately 1.3×10^7 m^3 of water is pumped out for irrigation, which had made the farms once abandoned due to seawater intrusion arable again (Zhang 2004). A groundwater water reservoir has also been constructed near the Dagu River to the northwest of Qingdao city. The length of the subsurface barrier was 3,398 m, and the potential storage capacity was approximately 1.46×10^8 m^3 (Lin et al. 2005).

The town of Sanjianpu, in Dalian, is located at a small intermountain basin. Approximately, 1.95×10^8 m^3 of runoff per year has been discharged into the sea through the narrow intermountain coastline (Chi et al. 2005). Meanwhile, excessive groundwater pumping has caused significant seawater intrusion problems, which have led to the contamination of groundwater in the shallow aquifer of this region. In 2002, the main part of the Sanjianpu project was completed. The project budget was more than 2×10^7 yuan, which was mainly spent on the construction of subsurface barriers, sluice gates, and infiltration trenches. The subsurface reservoir could increase the potential groundwater storage by 4.47×10^8 m^3 per year. It was estimated that the project budget was lower than the alternative long-distance water diversion project to solve the water resource problems. Kilometers away from Sanjianpu groundwater reservoir another project in Longhe was built. The subsurface barrier has a length of 545 m, and the capacity of

Fig. 5 Example photo of subsurface barrier in Shandong province

Table 1 List of groundwater reservoirs with subsurface barriers

ID	Project location	Total length of subsurface barrier (m)	Groundwater capacity (million m^3)	Cost (million yuan)	Completion year
P1	Longkou	6,000	54	42.5	1995
P2	Wang River	3,593	56	151.9	2004
P3	Dagu River	3,398	146	8.5	1997
P4	Longhe	545	0.87	4.1	2000
P5	Sanjianpu	~1,000	4.5	20	2002

the groundwater reservoir is about 8.7×10^5 m^3 (Zhu et al. 2008). Table 1 summarizes the information of five subsurface barriers mentioned above.

Freshwater lake in the intertidal zone

Instead of constructing subsurface barriers, the construction of a freshwater lake in the intertidal zone is an alternative method for preventing seawater intrusion and to retain discharged freshwater. A dam can be built at some offshore distance to form a closed lake between the dam and the original coastline. Immediately after construction, the saltwater is pumped out or flushed out by fresh river water. The lake will be filled by freshwater, which may be outflowing freshwater seepage, precipitation, and runoff or overland flow during floods (Hegnauer 2011). This additional freshwater may be of particular importance for water supply in small islands.

A good example can be found in the coastal village in Laizhou, Shandong Province, China (He et al. 2002). This area also relies upon groundwater as the major water supply, and groundwater has been excessively pumped here. In 1994, after a few years of drought, seawater intruded inland at a distance of 1,500 m, and 70 % of the wells were contaminated by seawater. As a result, 68 % of the farmland was intruded by seawater, which significantly reduced agriculture productivity. Many villagers had to travel a few kilometers to fetch freshwater for domestic use. Between 1995 and 1997, the farmers built a 3,700 m U-shaped dam in the intertidal zone, which pushed the sea-land boundary seaward by 1,300 m. In the new area reclaimed behind the dam, the farmers produced a freshwater lake of 0.33 km^2, freshwater aquaculture farms of 2 km^2, and a belt of well-treed windbreaks with a total area of 0.07 km^2. An artificial river of 1,200 m was constructed to direct the river water and possible rainwater to the freshwater reservoir and the aquaculture farm. As a result of the dam construction and the freshwater reservoir and aquaculture farms, the groundwater salinity was significantly reduced and the ecological environment was considerably improved. This coastal area originally suffering from seawater intrusion became a land of rich agriculture and fishery.

In summary, attempts to mitigate seawater intrusion have been made in the area around the Bohai Sea, and the effects have proved satisfactory over the years. It is noted that long-term maintenance is important to keep facilities functional. In addition to groundwater management projects, land reclamation in coastal areas can also impede seawater intrusion. China has conducted coastal land reclamation in large area for the expansion of port and city since 1950s. The analytical study by Guo and Jiao (2007) shows that after reclamation, the groundwater table rises and the saltwater–freshwater interface retreats seawards. The degree of these changes depends on the extent of reclamation and the hydraulic conductivity of the fill material.

Future prospects

Research on seawater intrusion in China has become most active over the past 30 years. Management projects have achieved good results in the prevention of seawater intrusion. The dependence on groundwater has been reduced in some regions; however, there are still many challenges related to the issue of seawater intrusion in China. Despite the control of population growth, the water resource consumption per capita in China will continue increasing with the process of industrialization. In additions, better groundwater management in coastal areas is required to be prepared for the uncertainties of climate change, including sea level rise.

The central government has initiated several large-scale projects in an attempt to solve the water scarcity problem. One of these projects is the south-to-north water division project (NSBD) (Chen et al. 2002). The basic idea of the NSBD is to divert water from southern China, mainly from the Changjiang River, to the drainage basins in northern China. The whole project includes three subprojects, the East Route, Middle Route, and West Route. The East and Middle Routes are currently under construction, with a designed annual supply of as much as 2.1–2.8 $\times$ 10^{10} m^3 and a total budget of 1.82 $\times$ 10^{11} yuan (in 2000). The completion of these projects will result in the reduction of groundwater exploitation will definitely be reduced, and the extent of seawater intrusion in the northern coastal regions. However, there are arguments concerning the economy and the impact of the project on the environment (Berkoff 2003).

For the future planning of seawater intrusion management of China, a more elaborate groundwater monitoring network is an important prerequisite in the coastal area. The modern monitoring system requires not only wells with multi-depth screens and sensors, but also an automatically stored database system with convenient access for scholars and the public (Jørgensen and Stockmarr 2009). In terms of the issue of groundwater management, the optimization techniques have been brought in for more than 20 years (Willis and Yeh 1987) and applied in the field, such as the optimization scenarios for improving seawater barrier operation in southern California (Bray and Yeh 2008). No matter what strategy China will make to improve groundwater management of coastal aquifers, the economic and environmental targets should be considered. These issues are closely related to the communities, and further studies are needed on a case-by-case basis.

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