Postprint on Groundwater Resource Issues and Seawater Intrusion Prevention and Control in China' s Key Coastal Zones

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Abstract

Due to the unique geographical and geological conditions of coastal zones, the environmental carrying capacity of groundwater resources in China's key coastal areas is fragile. In recent years, accelerated coastal engineering projects such as land reclamation have resulted in frequent environmental hydrogeological issues in coastal zones and ecological environment deterioration, which has severely constrained ecological construction in China' s coastal zones. This article analyzes the environmental hydrogeological characteristics of China' s coastal zones, examines the current status of groundwater demand in coastal zones and the primary geological environmental problems arising from unreasonable groundwater exploitation, and indicates that water resource shortages and ecological environment degradation resulting from seawater (saline water) intrusion will severely restrict the sustainable development of China' s coastal zones. How to scientifically promote the coordinated development of groundwater resources and the environment has become a crucial strategic task for the integrated management of China' s coastal zones.

Full Text

Groundwater Resource Issues and Seawater Intrusion Prevention in China' s Key Coastal Zones

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Abstract

Due to the unique geographical and geological conditions of coastal zones, the environmental carrying capacity of groundwater resources in China's key coastal areas is fragile. In recent years, accelerated coastal engineering projects such as land reclamation have triggered frequent environmental hydrogeological problems and ecological deterioration, severely constraining ecological development in China' s coastal zones. This paper analyzes the hydrogeological characteristics of coastal environments, examines current groundwater demand and the major geological environmental issues arising from unreasonable exploitation, and concludes that water shortages and ecological degradation caused by seawater (saline water) intrusion will seriously restrict sustainable coastal development. Scientifically promoting coordinated development between groundwater resources and the environment has become a critical strategic task for integrated coastal zone management in China.

Keywords: coastal zone, geology, groundwater, seawater (saline water) intrusion

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1. Research History and Current Status

Research on coastal groundwater and seawater intrusion began in the 19th century, with J. Du. Commun, Badon Ghyben, and Herzberg independently deriving mathematical expressions for the depth of the freshwater-saltwater interface below sea level in 1828, 1889, and 1901, respectively [4]. Since the 1940s, Australia has conducted specialized monitoring of seawater intrusion in coastal cities like Melbourne and Sydney, implementing water management plans and engineering measures that have achieved some mitigation. In 1965, the Polytechnic University of Barcelona began systematic research on groundwater flow-salinity relationships, seawater intrusion prediction, management, and control along Spain' s Mediterranean coast [4]. During the latter half of the 20th century, Japanese scholars proposed water conservation regulations and prevention measures through long-term monitoring of seawater intrusion in Fuji and Osaka. Bear discussed approximate solutions for stable and moving interfaces and the upcoming problem caused by pumping from wells at the interface in *Dynamics of Fluids in Porous Media* (1972) and *Hydraulics of Groundwater* (1979). The 18th International Association of Hydrogeologists (IAH) conference held in Cambridge in 1985 comprehensively addressed research status, fundamental principles, geological conditions, groundwater exploitation, calculation methods, monitoring techniques, and freshwater resource management in coastal areas [5]. UNESCO published Custodio' s *Groundwater Problems in Coastal Areas* in 1987 to encourage further scientific research on seawater intrusion. In recent years, countries including the United States, Japan, the Netherlands, Spain, Australia, and Mexico have deepened their understanding of coastal groundwater evolution through investigation and monitoring, advancing research on influence mechanisms, monitoring, and development trends.

China' s research on seawater (saline water) intrusion began in 1975, focusing on the Bohai Bay region with specialized investigations into coastal groundwater and intrusion phenomena [10]. Early work emphasized numerical simulation methods [11], established groundwater quality models to study salt-freshwater interface migration [12], and conducted applied research on intrusion mechanisms using multiple environmental tracers to advance understanding of paleohydrogeological evolution [13,14]. Li Hailong conducted multi-component, multiphase flow hydrogeological studies in the Laizhou Bay and Jiaozhou Bay areas [15]. China has since made significant progress in seawater intrusion prevention and control [6-9]. The Ministry of Science and Technology and other agencies jointly formulated the *National Water Security Innovation Engineering Implementation Plan (2015-2020)*, which includes research on groundwater management and seawater intrusion prevention in the Yellow Sea and Bohai coastal regions, aiming to develop control technologies for coastal groundwater exploitation and comprehensive intrusion prevention.

2. Main Geological Characteristics of China' s Coastal Zones

China' s mainland coastal zone exhibits distinctive north-south climatic zoning and geological features, spanning 22 latitudes with precipitation decreasing significantly from south to north while evaporation and aridity coefficients increase [16]. Due to rapid uplift of the Qinghai-Tibet Plateau in the early Quaternary, rivers flowing eastward carried substantially greater sediment loads. Mud and sand were continuously transported to estuaries and coastal areas for deposition, with substantial portions redistributed by alongshore currents to adjacent coasts. Consequently, terrestrial geological processes represent the dominant force controlling coastal zone formation, development, and evolution, while marine processes play only a modifying role [16].

Influenced by tectonic stress from the Pacific and Indian Ocean plates, China' s offshore marginal and intraplate geological structures along the eastern Eurasian plate margin are highly active [17]. The coastal zone has experienced dramatic changes, particularly during the Quaternary with frequent global climate alternations. According to Liu Xiqing et al. [18], north of Hangzhou Bay' s southern side, vertical coastal movement is strong and deformation complex, controlled primarily by NE-trending structures with subsidence dominating (though Shanhaiguan and Shandong Peninsula uplift occur within this subsidence background). The subsidence rate is greatest along the Bohai Sea' s western coast (Tianjin-Cangzhou), characterized by tectonic subsidence and land subsidence induced by groundwater exploitation, forming the lower Liaohe, North China, and northern Jiangsu plains with Quaternary marine-terrestrial sediment layers hundreds of meters thick. The central boundary zone shows weak, stable vertical crustal movement with minimal uplift-subsidence variation. South of the boundary, coasts are dominated by uplift, mostly hilly coasts with small estuarine subsidence basins of low activity intensity, except for the Pearl River

Delta' s western region which shows subsidence.

China' s eastern coastal zone displays clear hydrogeological zoning with distinct groundwater characteristics [19]: (1) Plain coasts widely exhibit marine-terrestrial alternating sediment layers with complex interlayered fresh and saline water and complicated water quality types. (2) Conditions differ north and south of the Yangtze River mouth. South of the Yangtze (including the estuary), groundwater resources are abundant, while north of the estuary, coasts suffer from drought and relative scarcity of surface and groundwater. Southern coasts commonly show alternating fresh-saline water layers with residual saline lenses in freshwater layers, whereas northern coasts are dominated by shallow saline layers with deep freshwater layers in some areas. Carbonate rocks are widely distributed in southern coastal zones with developed karst, prone to karst collapse and seawater intrusion. Weathered crusts in some southern coastal zones locally reach 10–50 m thickness, representing a major cause of mountain collapse and soil erosion. (3) In many coastal cities, extensive groundwater exploitation has lowered dynamic water levels below sea level, causing seawater and saline water intrusion. (4) In estuarine delta subsidence plains, continuous coastal accretion combined with reduced river inflow has caused serious declines in freshwater resources and water quality deterioration.

3. Groundwater Resource Problems and Countermeasures in China' s Coastal Zones

3.1. Main Problems Approximately 20% of China' s water supply comes from groundwater, reaching 50–80% in the relatively dry North and Northwest China regions. However, groundwater quality is concerning: based on 2011 sampling from over 200 cities and districts, 55% of more than 4,700 groundwater samples were classified as Grade IV or V [20]. The full extent of nationwide groundwater pollution remains unquantified.

China' s eastern coastal zone is densely populated with rapidly developing economies and accelerating urbanization. Water resource problems—including uneven distribution (manifesting as resource-based or quality-based water scarcity), severe groundwater over-exploitation, and intensifying water pollution—have become critical constraints for coastal city development. Water source pollution has caused crop yield reductions, aquaculture losses, decreased industrial efficiency, drinking water difficulties, elevated heavy metals in food crops, rising cancer and gastrointestinal disease rates, and increasing water treatment costs [22]. In the Liaohe, Haihe, and Shandong coastal rivers, over 50% of river sections no longer meet agricultural irrigation standards, and organic chlorine pesticides and 30+ types of carcinogenic, teratogenic, and mutagenic substances have been detected in some Binzhou groundwater [21].

Nearly 40 years of reform and development in coastal areas demonstrate that rapidly developing coastal cities are often the most severely polluted [23]. Industrial and domestic pollution has spread from point sources to area sources and from urban to rural areas, with regional economic development levels showing synchronous growth with environmental pollution. The Bohai Rim region features dense urbanization and heavy industrial layouts, intensifying conflicts between water supply and demand and making rational water allocation a focal constraint on regional development. Although southern coastal zones like the Pearl River and Yangtze River deltas have abundant rainfall and dense river networks, intensified industrial and domestic pollution has also caused widespread quality-based water scarcity [23].

3.2. Management Approaches

(1) Adopt a holistic perspective. Treat surface water, groundwater, and soil as an integrated environmental system [24] and comprehensively consider coastal water cycling processes. Strengthen integrated watershed water resource development planning based on coastal groundwater distribution characteristics, optimize well field distribution to avoid local over-exploitation, and regulate groundwater levels and cone of depression morphology to gradually achieve dynamic equilibrium between recharge and extraction [25].

(2) Enhance coastal groundwater monitoring. Establish monitoring networks for groundwater level, quantity, and quality; improve monitoring technologies; develop dynamic groundwater databases; and utilize modern information systems to conduct in-depth investigations of coastal groundwater at different temporal scales to ensure sustainable utilization.

(3) Establish joint surface water-groundwater regulation mechanisms. Develop rational water allocation and scheduling plans based on inflow, storage, and demand to fully and reasonably exploit groundwater resources [25]. Conduct targeted groundwater recharge in over-exploited areas to restore or raise water levels and increase recharge, based on typical coastal water resource distribution characteristics.

(4) Combine source development and conservation. As coastal groundwater demand continues increasing, implement the strictest water resource management systems and establish water-saving societies while developing new sources.

4. Distribution and Prevention of Seawater (Saline Water) Intrusion

Seawater (saline water) intrusion includes seawater intrusion, saline water intrusion, and saltwater wedge intrusion. Necessary conditions include hydraulic connection channels between seawater and terrestrial aquifers and hydraulic head differences. Primary causes include dynamic changes in seawater wedges driven by ocean tides, waves, and currents, with wedges advancing landward when abnormal pressure differences occur. Intrusion patterns correlate closely with coastal types: muddy coasts in the Bohai Rim (e.g., Liaoning Yingkou, Liaohe Delta, Tianjin Binhai, Hebei Cangzhou-Huanghua, Shandong Laizhou Bay) experience mainly saline water intrusion related to groundwater over-exploitation.

Yangtze and Pearl River mouth intrusions are dominated by saltwater wedge intrusion influenced by river discharge and tidal action. Sandy coasts in southeast China (e.g., Guangdong Zhanjiang, Guangxi Beihai, Qinjiang Delta, Hainan Danzhou Xinying Bay) and locations like Shandong Longkou, Hebei Beidaihe, and Liaoning Dalian experience primarily seawater intrusion.

4.1. Distribution Characteristics Since the 1970s, seawater (saline water) intrusion has occurred with increasing frequency in Liaoning, Hebei, Tianjin, Shandong, and Guangxi, particularly prominent in Dalian and northern Shandong [26]. The 1980s saw accelerated intrusion with expanded groundwater exploitation, forming a continuous intrusion zone along Laizhou Bay' s southern coast (Guangrao to Longkou) [27] and various-scale intrusions near major river mouths in Yantai, Weihai, Qingdao, and Rizhao. This represents a widespread and serious geological hazard. From 1991–2004, significant groundwater extraction and brine resource pumping expanded the saline water area to its maximum. During 2005–2014, stable precipitation and Yellow River water transfers caused the negative water level cone area to shrink continuously, slowing intrusion in some areas and locally stopping it.

Recent reduced precipitation and increased industrial/agricultural water demand have intensified groundwater extraction in some coastal areas, causing fluctuations in intrusion interfaces. The State Oceanic Administration' s *2015 China Marine Disaster Bulletin* documented these changes [28]. During 2011–2015, seawater intrusion distances increased in some monitoring zones of Liaoning Panjin and Huludao along the Bohai coast; the intrusion range gradually expanded in Jiangsu Lianyungang monitoring zones along the Yellow Sea coast; chloride concentrations increased significantly at nearshore stations in Fujian Changle Zhanggang Town along the East China Sea coast; and intrusion distances slowly increased in Guangdong Maoming Longshan monitoring zones along the South China Sea coast. By 2015, severe intrusion was mainly distributed in Bohai coastal plains, with 46% of monitoring zones showing intrusion distances of 10–43 km from shore, primarily along Hebei and Shandong coasts. Yellow Sea and East China Sea coastal zones showed smaller intrusion ranges, with about 86% of monitoring zones within 5 km of shore. South China Sea coastal zones exhibited small-scale, low-degree intrusion, with 90% of monitoring zones within 0.5 km of shore.

Laizhou Bay represents the most severely affected area in northern China [31], experiencing both seawater and saline water intrusion with typical characteristics. Intrusion depths along the coast mainly occur above 80–100 m, within multi-layered fluvial and alluvial sand layers with coarse grains, wide distribution, and good continuity, serving as primary intrusion conduits. Weakly permeable layers of silty clay and clayey silt separate sand layers, resulting in mainly lateral intrusion with some vertical intrusion in heavily pumped areas [29]. Analysis indicates that continuous drought, uneven water resource distribution, and coastal tidal/wave/current variations are background conditions;

aquifer hydraulic conductivity is a fundamental condition; and excessive groundwater exploitation causing large water level declines that destroy the natural salt-freshwater balance is the direct cause [30]. Numerous research institutions have conducted specialized investigations over the past 30 years, but monitoring typically ceases when projects end, hindering in-depth research and preventing timely provision of accurate intrusion forecasts to national authorities.

4.2. Prevention and Control Measures **(1) Rational groundwater exploitation.** Promote industrial water conservation and new water-saving irrigation technologies to transform agriculture and industry into water-saving models. Establish water resource management models to optimize exploitation in coastal cities.

(2) Construct underground reservoirs. Coastal underground reservoirs include mountain valley, alluvial fan, and buried paleochannel types. These reservoirs can both prevent seawater (saline water) intrusion and store freshwater. Northern coastal areas have favorable conditions and substantial development potential [33]. Rational construction and management of underground reservoirs effectively increase water availability in water-scarce northern coastal regions. Shandong Peninsula has built reservoirs including Laizhou Wanghe, Huangshuihe, Longko Balishahe, Qingdao Daguhe, and Yantai Jiahe. Through temporal-spatial optimization and joint regulation, scientific management of underground reservoirs will effectively improve soil and water quality, prevent intrusion, and enhance ecological hydrological environments for long-term freshwater utilization.

(3) Inter-basin water transfer. For key coastal zones unable to solve water shortages locally, timely construction of inter-basin transfer projects should maintain and restore groundwater-seawater dynamic balance, prevent intrusion, and alleviate urban water shortages. Qingdao' s "Yellow River to Qingdao" project played an important role in intrusion prevention.

(4) Artificial groundwater recharge. Recharging with fresh water can raise water levels and flow velocities, using freshwater pressure to force seawater retreat—an effective intrusion prevention method. The Netherlands fully utilizes river inflow for artificial recharge to maintain coastal groundwater dynamic balance.

(5) Establish monitoring and forecasting systems. Build seawater (saline water) intrusion monitoring research bases and well networks in key areas with real-time online monitoring to develop prediction models for effective prevention [32].

5. Conclusions and Recommendations

Under natural factors including global climate change, sea level rise, and uneven land subsidence, coastal engineering activities are becoming more frequent, making seawater (saline water) intrusion inevitable, concealed, variable, and difficult to control. Water resource and environmental effects are increasingly impacting typical coastal engineering and economic development, warranting sufficient attention.

Given coastal groundwater resource and environmental geological problems caused by unreasonable exploitation, future work should: conduct comparative geological hazard analysis from a regional water cycle perspective; clarify directions for sustainable groundwater utilization (including brackish water, saline water, brine, and mineral water development, island groundwater, and emergency water source establishment) and environmental geological hazard prevention; conduct coastal groundwater research based on current economic and social development needs; and predict and evaluate future water environment trends to propose prevention measures.

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Note: Figure translations are in progress. See original paper for figures.