Research on the analysis and management measures of land subsidence caused by groundwater exploitation in Tianjin, China

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Abstract. Since the 20th century, there has been an increasing reliance on groundwater due to the rapid development of agriculture and industry. This has resulted in the exploitation of groundwater in large quantities, leading to global land subsidence problems. Tianjin is one of the cities where this problem first emerged, but few studies and surveys have been conducted. As a result, the lack of management of groundwater extraction has caused the issue of land subsidence to become more prominent in recent years. By investigating and collating global research on land subsidence problems caused by groundwater extraction, it is concluded that mathematical and numerical methods, global information systems, remote sensing, and other technologies can be utilized to monitor and predict groundwater levels. Regional management measures can then be developed based on simulation results. However, the application of such technology in Tianjin is insufficient, and there is a need to strengthen the connection between management measures and research data analysis results.

Keywords: Groundwater exploitation, Land subsidence, Environmental monitoring, Groundwater management

1. Introduction

Groundwater refers to the water that fills the small spaces between rocks, soil, and sediments, which is stored below the Earth's surface. Groundwater affects and provides domestic water for more than 5 billion people and is also the main resource for irrigation [1]. Humans have been utilizing groundwater for millennia, which is essential for survival. Furthermore, humans tend to pump more groundwater during droughts, especially in regions with significant population growth. In the last century, easy access to pumped wells has led to a global surge in the use of groundwater for municipal, industrial, and agricultural purposes. Many major aquifers around the world are being depleted due to excessive groundwater pumping, which is happening at a faster rate than natural replenishment can keep up with. This ongoing depletion is expected to exacerbate midlatitude drying in various regions, including North Africa, the Middle East, South and Central Asia, North China, North America, Australia, and other specific areas worldwide [2]. This phenomenon causes several issues, including land surface subsidence, streamflow depletion, sea-level rise, seawater intrusion, even ecological damage, and regional climate feedback from irrigation [3]. Land subsidence is a major issue in densely populated deltaic regions, causing widespread environmental and protection concerns. More than 40 states in the USA and over 90 cities in China are affected by this problem [4]. Additionally, there are 15 low-lying coastal cities, including Tianjin, that are at risk of shrinking and being inundated by the end of this century due to subsidence. The issue of ground subsidence is progressively impacting urban development and management, and even posing a threat to the lives of residents. This article discusses Tianjin's current land subsidence problem, and analyzes its groundwater monitoring and management, and proposes future management directions based on global land subsidence research. It proposes a sensible plan for managing groundwater in Tianjin, providing clues for future solutions to the land subsidence caused by groundwater overexploitation.

2. Global groundwater mining detriment and remedial measures

Initially, pumping was derived from the removal of water from storage, which was small and could be recharged in small quantities by renewable aquifers. But over time, more and more of the pumping comes from a reduction in discharge or an increase in recharge. It is worth noting that once the new equilibrium is reached, no additional water is removed from storage [2]. In fossil or compacted aquifers, recharge is broadly divided into situations where recharge is unavailable and where recharge cannot refill drained void spaces; in regenerative aquifers, regeneration The amount is far less than the mining amount, and the water head continues to decline significantly, resulting in the permanent depletion of the aquifer, which in turn triggers land subsidence.

2.1. The potential land subsidence caused by the excessive use of global groundwater

The exploitation of most of the largest aquifers on land is causing irreversible depletion of these valuable resources. Some of these aquifers, such as the North China Plain, the Guarani Aquifer in South America, the High Plains of the United States, the Canning Basin in Australia, the Northwest Sahara Aquifer System, and the aquifers in Northwest India and the Middle East. Among these, aquifer depletion is particularly severe in Northwest India, the North China Plain, the central United States, and California.

In the 1920s, excessive groundwater pumping resulted in a decline in fluid pressure and irreversible compaction of low-permeability materials within or near developed aquifers, leading to land subsidence. Initially observed in Shanghai and Tianjin, land subsidence problems have since been recorded in Mexico City, Bangkok, and various other locations [5-6]. In confined aquifer systems, the amount of water produced by irreversible aquifer compaction is typically equal to the amount of ground subsidence, which ranges from 10% to 30% of the total pumped water [7]. Recent research has shown that approximately 50% of the areas with frequent subsidence are located in the coastal plain and nearshore areas of major rivers downstream. The inland areas, particularly the front basin, come next, followed by mountainous areas. The areas between mountains or valleys account for only about 15% of the subsidence cases. In delta areas like the North Nile Delta in Egypt, the Tiber Delta in Italy, the Fraser River in Canada, the South Yangtze River Delta in China, the Mekong Delta in Vietnam, the Yellow River Delta in China, and the Waal River Delta in France, the alluvial sediments are usually finely graded, which further exacerbates ground subsidence.

2.2. Management measures and monitoring methods for land subsidence areas

The assessment of the rate of groundwater depletion and the factors influencing it is a complex task. One example is the impact of declining groundwater levels, which not only reduces the recharge of groundwater to rivers, wetlands, and springs, but also affects the ability of aquatic plants near these areas to access groundwater. When a river is connected to an aquifer, the reduction in groundwater can lead to a decrease in flow into the river, or the groundwater aquifer may induce infiltration from the river, further reducing its flow. Differentiating between the causes of runoff depletion in rivers that are already heavily impacted by excessive diversion of surface water can be challenging. Similarly, determining the source of groundwater extraction from confined aquifers can be complicated, as it may involve leakage from adjacent confined formations, and monitoring and estimating the depletion of low-permeability formations is a difficult task.

Currently, groundwater extraction and changes in groundwater levels are being monitored and managed worldwide. The monitoring methods primarily involve mathematical and numerical techniques, global information systems, and remote sensing technologies.

Mathematical and numerical methods are employed to forecast or monitor fluctuations in groundwater levels through the construction of precise three-dimensional models that simulate aquifer systems. These numerical models are frequently utilized to estimate water quality projections for regional aquifer systems. The models are meticulously designed and developed based on sound hydrogeological assessments, and they are calibrated to accurately represent pre-design and development conditions. This enables the models to predict and assess future groundwater quality conditions and trends.

Remote sensing mapping technology plays a crucial role in monitoring spatiotemporal changes in groundwater. By utilizing satellite remote sensing technology, we can acquire valuable parameters such as surface temperature and soil moisture across a wide area, enabling us to indirectly assess fluctuations in groundwater levels. These remote sensing data can be integrated with on-site ground observations, computer models, mathematical statistical methods, and global information systems(GIS) to develop a simulation model that accurately represents the spatiotemporal changes in groundwater. Evaluating groundwater reserves is a significant aspect of assessing the availability and scarcity of groundwater resources. Remote sensing mapping technology can also contribute to this assessment. By monitoring surface changes using remote sensing technology, we can deduce the evolving trends in groundwater reserves.

3. Examining the overuse of groundwater in Tianjin

3.1. Geographical conditions of Tianjin

Tianjin is located in North China, in the northeast of the North China Plain, in the lower reaches of the Haihe River Basin, at the confluence and estuary of the five major tributaries of the Haihe River (South Canal, Ziya River, Daqing River, Yongding River, and North Canal). Yanshan is adjacent to the capital Beijing in the west and Hebei Province in the rest. It is located between 116°43’ to 118°04’ east longitude and 38°34’ to 40°15’ north latitude. The general terrain of Tianjin is high in the north and low in the south, high in the west and low in the east. The highest point in the city is Jiushan Peak, Jizhou District, with an altitude of 1078.5 meters, and the lowest point is Dagukou, Binhai New Area, with an altitude of 0. The average altitude is 3 meters. It is a warm temperate semi-humid monsoon climate with four distinct seasons.

3.2. Hydrogeological conditions of Tianjin

In the Tianjin Plain, there are five aquifer groups in the unconsolidated layer. The first three belong to the Quaternary period, while the last two belong to the upper part of the Neogene period. The floors of each aquifer group are buried at depths ranging from 40-60m to 550-600m. The plain can be divided into three parts: the Piedmont alluvial-diluvial slope plain, the central alluvial-lacustrine plain, and the coastal alluvial-marine plain. The central alluvial lacustrine plain and the coastal alluvial marine plain, which cover an area of 9218 km2, have underground saline water that is continuously distributed. The depth of the saline layer’s bottom plate -- Deep groundwater refers to the freshwater found underground below the saline layer, including the groundwater of each aquifer group below the middle section of the second aquifer group -- varies from 40-200m, depending on the location [8].

Tianjin is facing a severe shortage of water resources, with an uneven distribution. The city relies heavily on a centralized water supply that originates from a single source, which accounts for only one-sixth of the country’s total water resources. Groundwater has emerged as a significant water source in Tianjin, but after several decades of exploitation for residential use and irrigation, its availability has nearly depleted. Moreover, the consolidation of sediments and the subsequent movement of underground materials have led to the irreversible phenomenon of land subsidence, causing certain areas of the surface to sink slowly or rapidly.

3.3. Management measures of groundwater exploitation and land subsidence in Tianjin

Deep groundwater mining in Tianjin has been ongoing since the early 20th century, with an annual mining volume of approximately 40,000 m3. It is primarily utilized for industrial production and only occasionally for urban tap water. By the mid-20th century, there was a growing number of motor-driven wells in both urban and rural areas. Shallow groundwater extraction was predominant in the north, while deep groundwater extraction was more common in the south. As deep groundwater extraction continues to increase, it leads to a decline in the groundwater level and subsequent land subsidence.

Land subsidence is a significant geological and environmental issue in Tianjin, characterized by a scarcity of water resources [9]. The inadequate supply of surface water sources necessitates heavy reliance on groundwater for industrial and agricultural production, as well as domestic water consumption. Subsidence, as a gradual and irreversible regional geological disaster in Tianjin, has resulted in various problems including a decline in ground elevation, diminished flood and drainage capacity of rivers, increased vulnerability to storm surge hazards, and compromised rail transit safety. The consequences of these issues are extensive and long-lasting.

Considering Tianjin’s geographical and hydrogeological conditions, existing research suggests that effective prevention and control of land subsidence in Tianjin can be achieved through strict control of overexploitation of groundwater resources and conservation and restoration of groundwater water-bearing systems [10]. The current methods of extracting groundwater involve formulating extraction indicators, conducting thorough reviews and approvals for new water extraction projects, implementing planned yearly extraction from existing wells, and actively promoting water source conversion projects to substitute groundwater with surface water [11]. In recent times, the South-to-North Water Diversion and the comprehensive management of groundwater overexploitation have helped to alleviate the declining trend of groundwater levels in Tianjin. However, the groundwater levels are still declining, and monitoring them is challenging. As a result, there have been several studies conducted to develop spatially distributed methods to quantify the multifunctional properties of groundwater and monitor the real-time health status of groundwater levels. This is used to mitigate the probability and risk of land subsidence.

4. Conclusion

This study focuses on the development characteristics of land subsidence and groundwater flow systems in Tianjin. Through a comprehensive analysis and discussion, the evaluation of over-exploitation situations is conducted based on hydrogeological units. It is concluded that groundwater in Tianjin’s subsidence area has been over-exploited as a whole. Nowadays, the issue of land subsidence has become a widespread ecological problem around the world. However, the detection and management of groundwater extraction still have room for improvement. This paper has not yet investigated the correlation between groundwater and land subsidence along with other contributing factors. Researchers must prioritize finding solutions to repair the problem of ground subsidence caused by excessive groundwater exploitation. The focus should be on reversing the declining trend of groundwater levels.

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