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ORIGINAL ARTICLE

Land subsidence in Tianjin, China

Yi Lixin · Zhang Fang · Xu He · Chen Shijie · Wang Wei · Yu Qiang

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Abstract Land subsidence has been affecting Tianjin for the past 50 years. It leads to comprehensive detrimental effects on society, the economy and natural environment. Overpumping of groundwater is the main cause. In 2008, the maximum cumulative subsidence reached 3.22 m and the total affected area nearly 8,000 km^2. The subsidence reached its most critical state in the early 1980s when it occurred at a rate as high as 110 mm/year. At the same time, groundwater extraction had also reached a maximum of 1,200 million m^3. By importing the Luan River to Tianjin and restricting exploitation of groundwater, hydraulic heads gradually recovered after 1986 in all aquifers, and this has continued to the present in the second aquifer. The subsidence rate in urban areas dropped to 10–15 mm/year. The area of groundwater extraction expanded to the suburban area with economic growth in the 1990s, and it was shifted to the third and fourth aquifers. At present, with a subsidence rate of 30–40 mm/year, four new suburban subsidence centers have been formed. Several measures were adopted to mitigate and prevent land subsidence disasters. These included restricting groundwater exploitation, groundwater injection, prohibiting use in the specific zone, a pricing policy for water resources, advocating water-saving technology, and strict enforcement of groundwater laws. Although the subsidence area is still increasing slowly, the subsidence rate is being controlled.

Y. Lixin (✉) · Z. Fang · X. He · C. Shijie
College of Environmental Science and Engineering, Nankai Univeristy, Tianjin 300071, China
e-mail: yilixin@nankai.edu.cn

W. Wei · Y. Qiang
Land Subsidence Control Office of Tianjin City, Tianjin 300061, China

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Introduction

Land subsidence is a common human-induced hazard caused by excessive exploitation of groundwater and petroleum, as well as mining (Holzer and Johnson 1985; Singh 1992; Hu et al. 2004; Xue et al. 2005). As it may cause geological, hydrogeological, environmental and/or economic impacts (Holzer and Johnson 1985; Holla and Barclay 2000; Abidin et al. 2008; Phien-wej et al. 2006; Wang et al. 2009; Wu et al. 2008), land subsidence attracts much attention from the government, community, industry and academia. Although it cannot be completely avoided in groundwater resource-dependent areas, it can be controlled more sustainably through governmental legislation, monitoring, industrial plans and technological advances (Singh 1992; Abidin et al. 2008; Hu et al. 2004; Zhang et al. 2007). This paper presents a case study of land subsidence caused by excessive groundwater pumping in Tianjin City, China.

In China, land subsidence is currently occurring primarily in 17 provinces (cities) in the eastern and middle regions of the country, including Shanghai, Tianjin and Jiangsu, and Hebei provinces; the total subsidence area is more than 7.9×10^4 km^2 (Sun 2002; Hu et al. 2004). Tianjin is the third largest city and the cradle of industrial modernization in China. In the process of urbanization, Tianjin has experienced extensive groundwater withdrawal for water resources, and this has induced disasters such as land subsidence and groundwater quality deterioration. At present, Tianjin is the city with the most serious land subsidence problems in China. Ground subsidence has become a major factor restricting sustainable and harmonious regional development. China's central government and Tianjin's local government have invested a large amount of money in the prevention and mitigation of these disasters. In 2005, China's central government issued a new social and economic development plan for the metropolitan area of Tianjin. This area will be developed as the economic center of northern China according to the new plan. A rapid increase of the population and extensive exploitation activities will take place in the near future in Tianjin, particularly in the costal zone.

In this study, the history of groundwater exploitation and land subsidence evolution as well as their interrelations are presented and discussed. Methods for subsidence prevention and mitigation are introduced, and their remedial effects are evaluated. The experiences and lessons from the land subsidence control strategies and implemented process are evaluated. The results will be applicable to Tianjin and other coastal cities that are currently experiencing groundwater and land subsidence problems.

Geological and hydrogeological settings

With an area of 11,919.7 km^2, Tianjin is one of four municipalities in China. It is located at the extreme eastern region of the northern plain of China, bordering Beijing, the Chinese capital to the west, the Yanshan mountains in Hebei province to the north and the Bohai Ocean to the east (Fig. 1). The research area is about 9,200 km^2, including the central and southern portion of Tianjin, which is between 38°34′N–39°41′N latitude and 116°42′E–118°04′E longitude. It was chosen because of the extensive historical groundwater exploitation and land subsidence occurring in this region. The selected area is topographically classified into three categories: the northern and western part of diluvial and alluvial plain, the central part of the alluvial plain, and the eastern part of the coastal lowland plain.

Tectonically, Tianjin is located at a Meso-Cenozoic basin area that was filled up by continental Tertiary and Quaternary sediments (Zheng et al. 1990). At the beginning of the Paleogene period, the Himalayan Orogeny was initiated as the basin subsidence occurred quickly because of the fault depression tectonic movement (Hydrogeology and Engineering Geology Institute 1987). The Tertiary-Quaternary sedimentary series deposited varies from less than 1,000 m in the structural high located around the area of Tianjin City to more than 3,000–8,000 m, E-SE and W-NW of Tianjin.

The hydrogeological units of this area can be divided into the Quaternary aquifer system and the Tertiary aquifer system, which are insulating in the hydrodynamics. The Quaternary aquifer system ranges from the surface to

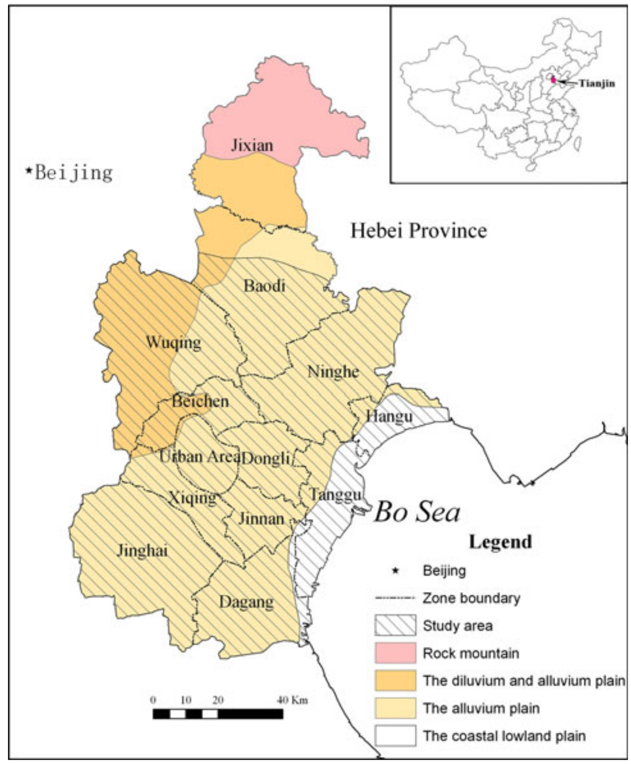

Fig. 1 The geographic location of the study area with indications of the geomorphologic zone

500 m, and the Tertiary aquifer system has a depth range from 500 to 1,100 m (Tianjin Geological Survey and Mine Resource Administration 1992; Angelo et al. 2008).

At present, groundwater abstraction is restricted to a depth shallower than 550 m below the ground surface in the entire region of the plain except for geothermal and oil extraction. Thus, the scope of this research focuses on exploitation of the Quaternary aquifer system and its relation to land subsidence.

Based on sedimentology with evidence from studies of sediment properties, dating, fossils, and permeability, the quaternary aquifer system was three-dimensionally discretized vertically into four hydrogeological units. Figure 2 shows the hydrogeological profiles in this area. Each unit can be conceptualized as an aquifer with an underlying aquitard. From the land surface downward, hydrogeological units I-IV have extents with a depth of 60–90, 160–210, 230–460, and 370–550 m, respectively. The continuous aquifer sand layer in each unit was about 10–20, 20–80, 40–50, and 40–60 m, respectively. Other impervious deposits including clays, conglomerates, and mudstones formed the aquitard. Unit I consists of both unconfined and confined regions. Most of the area is unconfined and comprises Holocene and Late Pleistocene deposits. Units II, III, and IV are all confined aquifers, and their stratums formed in the Middle Pleistocene, Early Pleistocene, and

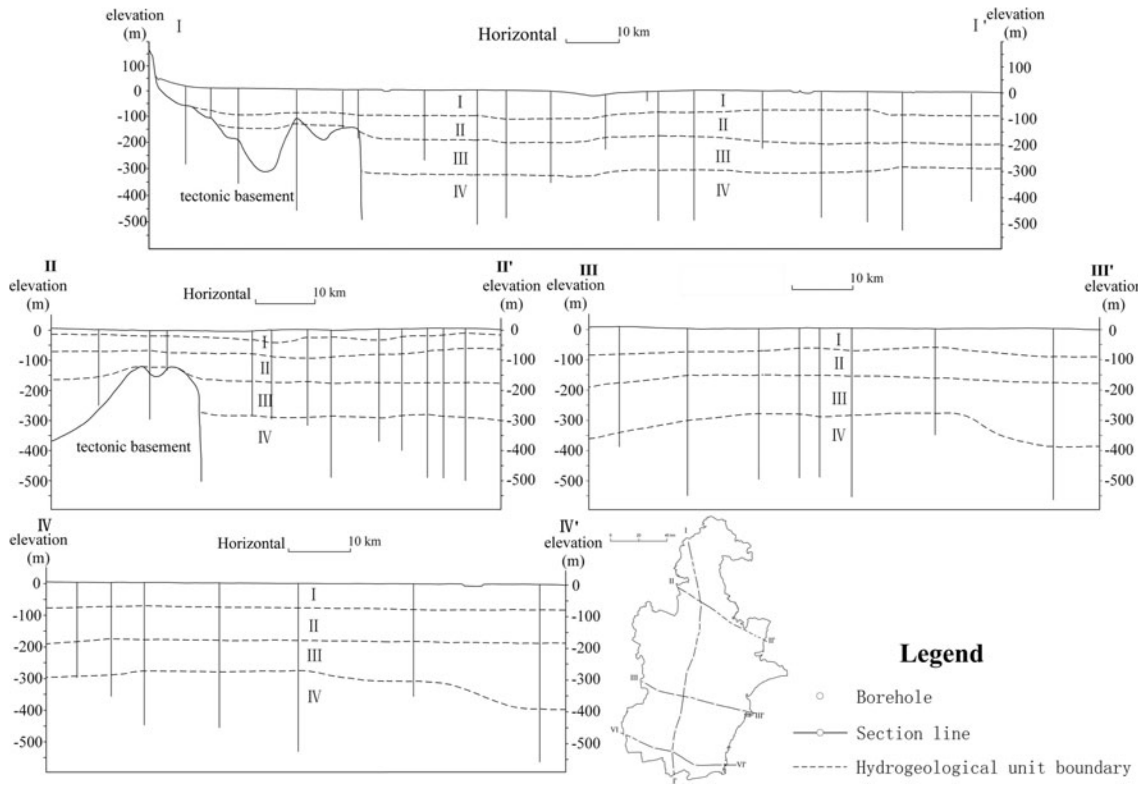

Fig. 2 The hydrogeological profiles in the study area

Late Pliocene periods, respectively (Tianjin Geological Survey Institute 2003).

History of groundwater withdrawal

Tianjin has the longest history of groundwater exploitation in China. The first water supply well was installed in 1898 in the urban area and in 1907 in the Tanggu district. By 1948, the total number of wells in Tianjin had reached 51, with a pumping volume of approximately 4×10^4 m^3/a (Tianjin Municipal Editorial Board of Local Chronicles 2004). The groundwater pumping yield has drastically increased since 1949 as a result of rapid economic development and urbanization. The history of groundwater withdrawal can be divided into three stages. The first stage is the period of continuous increase before 1981 as a result of economic development. The second stage is the period of rapid decrease from 1981 to 1988 that was attributed to the implementation of pumping regulations. The third stage refers to the gradual increase occurring after 1989 that has continued to the present.

The annual groundwater pumping volume from 1981 to 2007 is shown in Fig. 3. In the 1970s, the average pumping volume was 7.1×10^8 m^3/year; this number reached a maximum of up to 12×10^8 m^3/year in 1981. Thereafter,

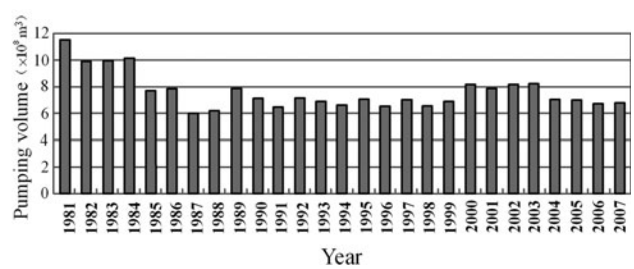

Fig. 3 Chart of the annual groundwater pumping volume in Tianjin City from 1980 to 2007

the pumping volume gradually decreased because of a water transporation project of the Luanhe River to Tianjin City that was completed in 1983. After 1988, it gradually, fluctuatingly increased, the extraction rate was stable in the 1990s, and the average yield was about 7.12×10^8 m^3/year. In recent years, the pumping volume has had a slowly decreasing trend and stayed at about 6.5×10^8 m^3/year.

An important feature of groundwater exploitation is the pumping aquifer change. Figure 4 shows the change of pumping rate and its percentage distribution in different aquifers in the urban area. As the diagram shows, urban groundwater pumping continues to decline. In the 1980s, the percentage of the second aquifer accounted for 50%-60% of the total exploitation amount; after that, this value has continued to decline and dropped to less than 10% in

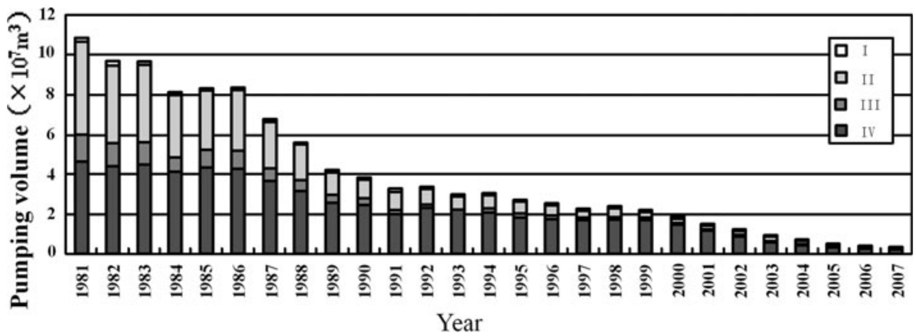

Fig. 4 Chart of annual groundwater pumping volume and its distribution in aquifers in the urban area from 1980 to 2007

2000. Conversely, the proportion of the fourth aquifer increased from 30–40% in the 1980s to 80% in 2000. Suburban groundwater exploitation has also undergone a change from shallow to deep. The current distribution of the amount of suburban exploitation shows the second, third, and fourth aquifers accounting for 20, 30, and 50%, respectively.

Groundwater exploitation in each district in Tianjin has a different process of change and at present has a different developmental trend, which is related to the severity of the measures implemented for groundwater management and the importation of substitute water resources. Groundwater withdrawal in the urban area is severely limited, and this region has preferential acquisition of imported water resources, so groundwater exploitation has continuously decreased since the 1980s. The rapid development of suburban industry in recent years and a relatively flexible limitation of groundwater exploitation have together led to new subsidence centers since 2000.

The distribution of the annual groundwater pumping intensity in each district is shown in Table 1. The pumping intensities of Jixian and Baodi in the northern part of Tianjin were larger than those of the other districts. However, because these two districts are located in bedrock areas, the groundwater exploitation did not induce noticeable land subsidence. Thus, this paper does not discuss these areas. Changes in groundwater pumping intensity in the urban areas (within the Outer Ring Road) are most significant: the highest pumping rate occurred in the 1970s, which was 33.38×10^4 m^3/a km^2 and reduced to an average of 20.72×10^4 m^3/a km^2 in the 1980s, which was mainly due to importation of external water resources and large-scale shutting down of wells. The pumping intensities were 4.68×10^4 and 4.52×10^4 m^3/a km^2 in the 1990s and the 2000s, respectively. This was mainly due to the continuing and strict implementation of groundwater exploitation management measures. In the suburbs, especially in the rapidly industrialized areas, such as Hangu, Beichen, Xiqing, Jinnan, and Dongli, groundwater exploitation has been increased significantly. Taking the Hangu District as an example, the average groundwater pumping intensity was 5.11×10^4, 13.09×10^4, 12.99×10^4, and 14.21×10^4 m^3/a km^2 in the 1970s, 1980s, 1990s, and 2000s, respectively. The distribution characteristics of groundwater exploitation mentioned above have resulted in stable land subsidence in the urban area, but rapid subsidence in the suburban area in recent years. Therefore, new subsidence centers have developed in the suburban area.

Table 1 Distribution of annual groundwater pumping intensity in each district from 1970 to 2000

	Average pumping intensity (1,000 m/a km^2)			
	1970s	1980s	1990s	2000s
Jixian	78.9	94.8	131.7	98.8
Baodi	80.3	78.7	81.2	91.9
Ninghe	33.5	36.5	47.3	74.4
Wuqing	39.7	62.2	74.4	72.7
Jinghai	54.3	52.8	35.3	40.6
Tanggu	60.0	75.6	24.1	27.5
Hanggu	51.1	130.9	129.9	142.1
Dagang	36.9	44.3	47.8	34.5
Beichen	35.7	49.1	49.6	50.2
Xiqing	22.3	56.6	82.2	64.4
Jinnan	60.0	112.0	91.7	81.4
Dongli	32.0	43.4	48.8	41.7
Urban	333.8	207.2	46.8	45.2

Land subsidence

From 1950 to 1957, the average subsidence was 7–12.0 mm/year in the urban area. From 1958 to 1966, it reached 30–46 mm/year. In this period, subsidence centers began to form in different places. From 1967 to 1985, the average subsidence rapidly reached 80–100 mm/year. After 1986, measures against land subsidence were taken. Accordingly, the rate in the urban area decreased to 10–15 mm/year, and land subsidence was mitigated in most of the urban areas. From 1959 to 2007, the maximum cumulative subsidence was 2.91 m in the urban area. Areas

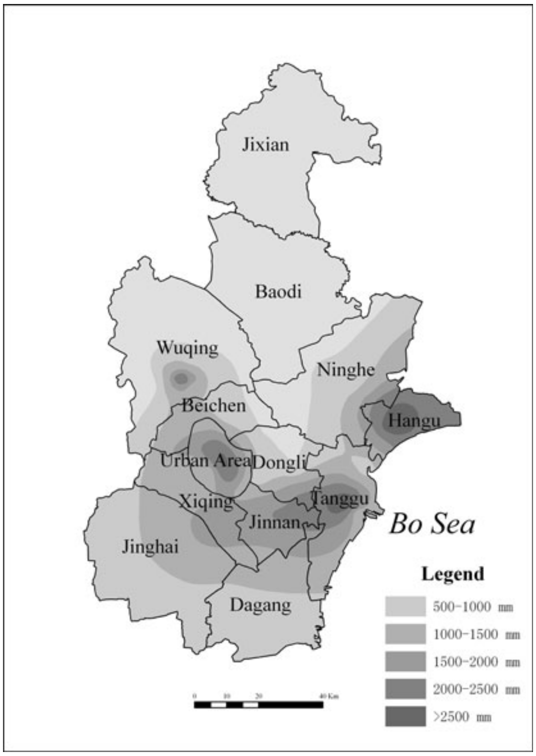

Fig. 5 Map of the cumulative land subsidence (mm) in the Tianjin metropolitan area from 1967 to 2000

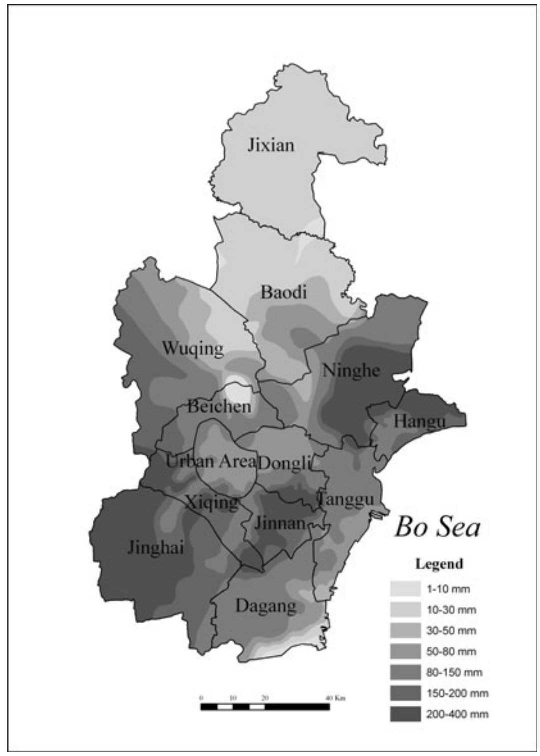

Fig. 6 Map of the cumulative land subsidence (mm) in the Tianjin metropolitan area from 2001 to 2007

with cumulative subsidence over 1.0 m account for 84% of the total urban area and 1.5–2.0 m for 42.3%. Areas of subsidence of more than 2.5 m have already reached 10.2 km^2. Figure 5 shows the cumulative subsidence from 1967 to 2000 in the Tianjin area.

Figure 6 shows the cumulative land subsidence from 2000 to 2007 in Tianjin City. As the figure shows, with economic development, groundwater exploitation has not been effectively controlled, and land subsidence has developed rapidly in the suburbs in recent years. In the Tanggu district, the average subsidence was 20–25 mm/year after 2000, and the maximum cumulative subsidence was 3.22 m from 1959 to 2007. In the Hangu district, the recent average subsidence was 35–45 mm/year, and the maximum cumulative subsidence was 3.08 m from 1959 to 2007. In the Wuqing district, the recent average subsidence was 35–45 mm/year, and the maximum cumulative subsidence was 2.1 m from 1959 to 2007. At present, there are four settlement centers: the urban center, Tanggu, Hangu, and Wuqing.

Mechanisms of land subsidence analysis

Pumping groundwater reduces pore water pressure in aquifers, usually with sand or conglomerate beds, which behave in a seemingly elastic manner (Karig and Hou 1992). However, this is followed by reduced pore water pressure in usually intercalated clay and aquitard materials in order to regain hydraulic equilibrium. Clay compaction is largely an irreversible, one-way process, and it is the major source of severe pumping-induced land subsidence (Terzaghi 1925; Holzer 1984; Phien-wej et al. 2006). When groundwater is recharged into the starved aquifers to recover the pore pressure, expansion of aquifer sand and gravel layers occurs and contributes to lifting up the ground surface as an elastic rebound (Waltham 2002). During piezometric head rises, the recharged sections of the aquifer release the formerly imposed compressive strain to show dilatation, producing elastic rebound. On the other hand, the starved sections of the aquifer and aquitard continue to show compression as the result of time-dependent consolidation behavior caused by past piezometric drawdown until the groundwater table has risen to remove deficits of pore pressure in these sections. Ground level change reflected in groundwater recovery is the competition between subsidence from the starved aquifer (plus aquitard) section and uplift from the recharged aquifer section (Chih et al. 2007).

Data of the annual groundwater pump rate and of the annual subsidence rate were collected to discuss the relationship between groundwater pumping and land subsidence (Tianjin Land Subsidence Control Office 1989–2005). Figure 7 illustrates the correlation between the groundwater

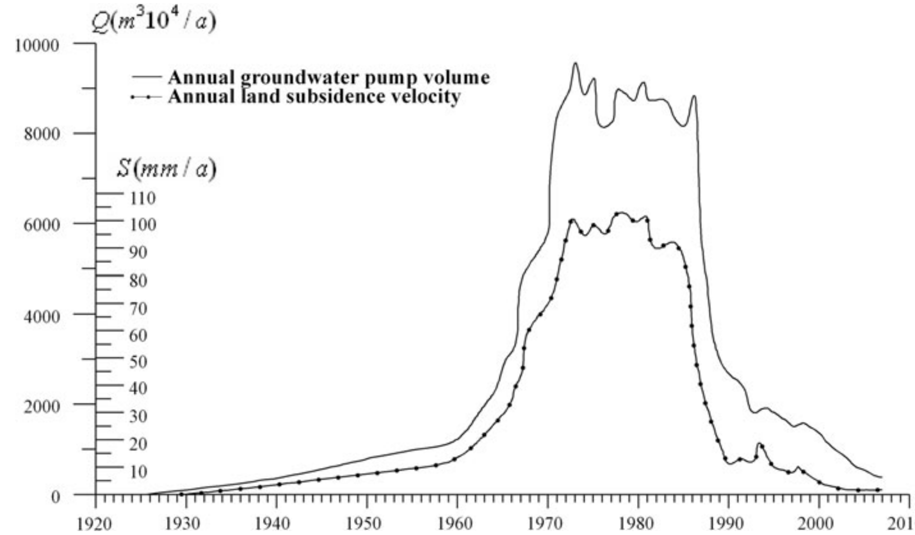

Fig. 7 The relation curve of annual land subsidence velocity and annual groundwater pump volume in the urban area

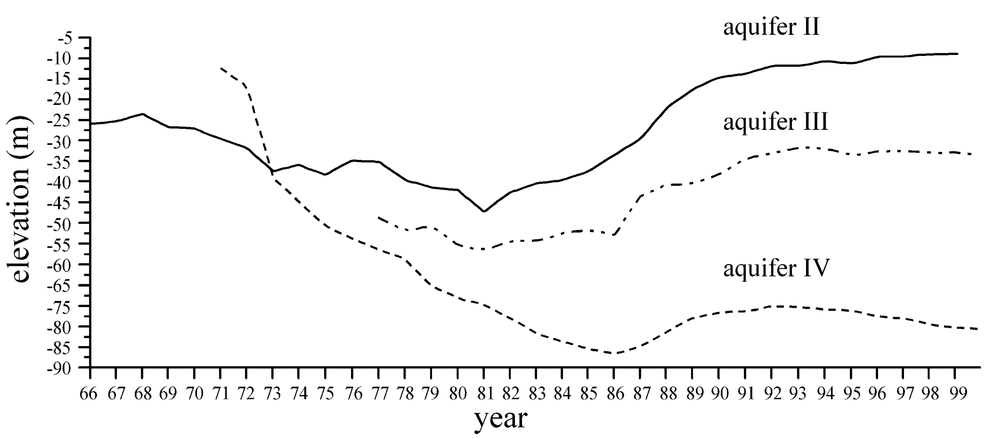

Fig. 8 The curves of groundwater levels in different aquifers

pumping rate and subsidence velocity in the urban area. It is clearly seen that these two numerical values correlate very well, indicating that the dominant cause of land subsidence in Tianjin is groundwater pumping.

Figure 8 illustrates the characteristics of the groundwater level changes in different aquifers; their locations are indicted in Fig. 10. The groundwater level started to rise as soon as the pumping was reduced in unit II in 1981, and in units III and IV in 1985. Since then, the tables of units II and III have continuously risen, but after a short period of rising, the table of unit IV has been decreasing. The changes in ground level reflect the situation of the pumping layers. The pumping yields from units II, III, and IV account for 7, 12, and 80%, respectively, of the total at present. The subsidence mechanism could be reasonably interpreted according to the above-mentioned principle. Compaction of units II and III during massive extraction would gradually be arrested following the recharge and sharp reduction of groundwater in the aquifer. Since 1985, as the levels have been climbing, deformation of units II and III has been becoming neutral as the rebound that had developed surpassed the remaining compaction. The uplift resulting from the elastic rebound of the aquifers has not been visible on the land surface until now. This phenomenon could be interpreted as the amount and rate of elastic rebound not outpacing the delayed clay compaction, and the rebound never came to full recovery of the ground depression because of land subsidence. In view of the scenario of heads in aquifers, it is reasonably inferred that land subsidence was caused primarily by clay compaction (delay consolidation) in hydrogeological units II and III and by sand compaction (elastic compaction) in unit IV.

Data from multilevel layers of compression monitoring wells proved that our speculation is correct. This monitoring group is located in the Tanggu district and consists of 12 wells. The location is indicted in Fig. 10. The pressure head and compression were simultaneously measured at each of the 12 levels, with the deepest monitoring level extending to 300 m and work starting in 1983. Figure 9a presents the cumulate compaction in the different hydrogeological units from 1983 to 1985. The cumulative surface subsidence was 346.2 mm during this time, and the

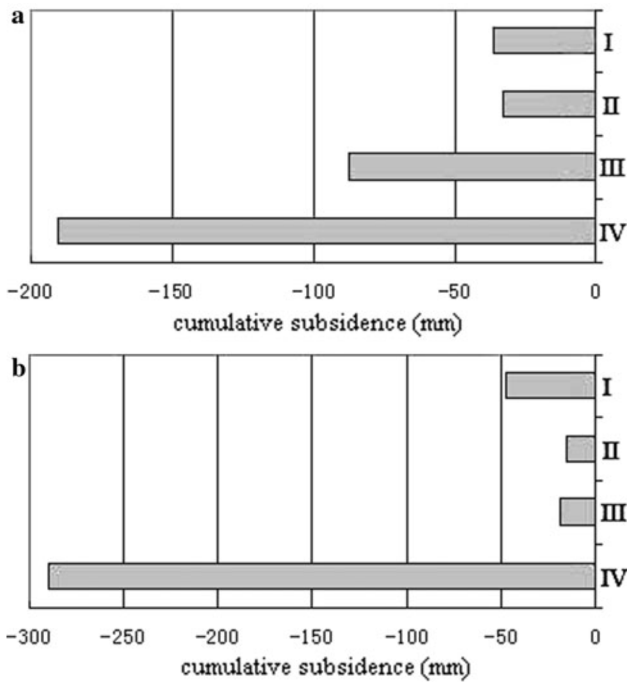

Fig. 9 Chart of cumulative subsidence distribution in different hydrogeological units

average annual subsidence was 115.4 mm. The ratio of hydrogeological compression of units I, II, III, and IV is 12.4, 7.9, 25.6, and 54.1%, respectively. After sharply reducing groundwater pumping in 1986, the annual subsidence declined to 31 mm. During the 12 years between 1986 and 2002, the cumulative subsidence was only 372.3 mm. Figure 9b illustrates the cumulate compaction distribution in the vertical profile from 1986 to 2002. As is shown, the ratio of units I, II, III, and IV is changed to 12.8, 3.5, 4.9, and 78.8%, respectively. Comparing Fig. 9a, b, it can be clearly seen that the ratio of compression of units II and III obviously declined, but for unit IV, it increased. An interesting phenomenon is that aquifer I had a duration compaction; in fact, the amount of pumping from aquifer I is small and only accounts for 1% of the total pumping volume. The compaction in aquifer I can be interpreted as soil consolidation and hydrocompaction.

Impacts of land subsidence in Tianjin

Land subsidence has extensive effects in Tianjin. A disastrous chain of events developed in the environmental system, with comprehensive negative impacts. The disasters and damage occurring in Tianjin municipality were as follows: (1) elevation resource loss; the value of the coastal land was diminished; (2) damage to buildings and civil structures, mainly to ancillary facilities such as pipelines and electric lines; (3) changes in the elevation and gradient of the stream channel and urban drain system, which led to decreases in their ability to discharge flood waters; the sewage of the city, which originally was drained by gravity, must now be drained by pumps. The flood discharge ability of the Haihe River has gradually weakened in recent years, decreasing from the designated 1,200 to 200 m^3/s (Jiang et al. 2008). (4) There have been failures of well casings and other water transport facilities, stream channels, and other water-transport structures requiring construction as well as repeated raising of levees to restrain flood waters. Many hundreds of irrigation wells failed because of compaction of the confined aquifer system. The irrigation system was damaged, and the reservoir capacity decreased. (5) There were increases of flooding frequency and tidal encroachment into lowlands in the coastal community; flooding worsened events always occurring in the urban area, and hurricane tides aggravated the scenario in the coastal area. (6) The net distance between the bridge and river decreased because of land subsidence, and this seriously affected the navigation of the riverway. There are 92 over-river bridges in Tianjin, with most of them inside the ring road. The height of 4 of 15 bridges over the main riverway had to be increased in order to allow navigation again. (7) Because of land subsidence, the erosion datum plane of the river was heightened, and the velocity of flow slowed. The gravity self-purification of the river lessened, and the water quality deteriorated.

Prevention and control of land subsidence

Realizing the serious hazards of land subsidence, Tianjin and the central government have carried out a systematic program of prevention and control since the 1970s. The approaches and measures taken are as follows.

Importing substitute surface water

In order to meet the increasing water needs of Tianjin, promote economic development, and control the further development of land subsidence, the central government invested in a project to import water from the Luanhe River (a river approximately 240 km from the city) to Tianjin City. This project was completed on 9 September 1983, and since then, it has been bringing 6×10^8 m^3/year of water into Tianjin (Jiang et al. 2008), accounting for 25% of the total water consumption in this city. The project guarantees the urban water supply and provides substitute water resources for land subsidence control. Land subsidence prevention and mitigation in the urban area would not have been achieved without importing water resources.

Limitations of groundwater exploitation

Controlling land subsidence in Tianjin by limiting groundwater extraction was started in 1986. From 1986 to 1997, Tianjin City implemented a 3-year subsidence control plan four times, with the main objective of sealing selective groundwater wells in areas of serious land subsidence. During these 12 years, 637 wells in the urban area and 175 wells in Tanggu district were closed. Reduced pumping was mainly controlled in units II and III. In 1986, the pumping volume was 8.2×10^7 m^3 in the urban area, and this number decreased to 2.1×10^7 m^3, while the volume in Tanggu was reduced from 9.0×10^7 to 2.0×10^7 m^3. After limitating groundwater extraction, the levels of aquifer systems II and III recovered gradually, and the subsidence rate decreased significantly.

Artificial recharge of aquifers

Repressuring of confined aquifer systems by artificial recharge directly through wells is an effective way to slow down or stop land subsidence. There are different uses of the artificial recharge of groundwater activities in Tianjin. For example, the textile mills inject cool surface water in the winter and withdraw it in the summer for air conditioning in the workshop, a practice that has been employed since the 1970s. Oil and geothermal exploitation always operates using artificial recharge to enhance oil production or sustainable geothermal resource utilization. Artificial recharge for land subsidence prevention and mitigation purposes began in 1985; from 1985 to 1996, about $1{,}608 \times 10^4$ m^3 of water was injected into the aquifers. The injection areas were limited in the urban area and Tanggu district, and injection into aquifers was limited in hydrological units II and III. After 1997, artificial recharge was stopped because of high costs.

Conservation in the application and use of water

In order to guarantee that land subsidence prevention and mitigation were successfully put into practice, and to meet the demand for water resources in economic development, groundwater exploitation was heavily cut back, while water-saving techniques were promoted. Firstly, 39 small-scale water storage projects were built from 1985 to 1997. At the same time, 46 rivers were desilted, and many ditches and channels were repaired. Through these works, the water storage capacity was increased by 2.27×10^8 m^3. Secondly, through improvement of irrigation methods, 7.4×10^8 m^3/year of water was saved in agricultural practices, and the irrigation area was decreased from 72.33×10^4 Mu in 1997 to 10.65×10^4 Mu in 2007. Thirdly, advanced water-saving techniques have been promoted in industry, and the water consumption of 10,000 Yuan industrial output value decreased from the 160.7 m^3 in 1985 to 50 m^3 in 1996. Fourthly, recirculation and reuse of treated water have been promoted, and the percentage of reused water increased from zero in 1985 to 15% in 2007. In addition, practical tests of urban wastewater recycling and the direct use of seawater and shallow ground saltwater for irrigation have been implemented.

Administrative measures

In order to coordinate the total social resources involved in the activities of land subsidence prevention and mitigation, a special joint committee was organized under the Tianjin government's Department of Construction Bureau in 1985, and in 1996, the Tianjin Control Land Subsidence Office was established. This office is the only standing body specifically responsible for land subsidence control in the local government in China. Under the joint committee there are four professional groups: the subsidence monitoring group, geological survey and groundwater level monitoring group, urban groundwater pumping reduction methods group, and suburban groundwater pumping reduction methods group. The groups' personnel comes from various government departments, such as the geological bureau, water conservation bureau, construction plan bureau, public services bureau, etc. In the process of land subsidence control, the joint committee set a goal for groundwater pumping reduction and land surface settlement velocity reduction at every stage in each sub-region; professional groups formulated the technological scheme and response for implementing it. Through 12 years (1985–1997) of continuous effort, the serious land subsidence trend in the urban area was effectively controlled.

Economic control

Concerning economic measures in land subsidence control, the main approach is adjusting the price of groundwater resources to promote the reduction of groundwater pumping and the application of water-saving technology. In 1997, the price of tap water for industry was 0.05 Yuan/m^3. In order to apply economic levers to promote subsidence control, the price of groundwater has been adjusted to 2.0–2.6 Yuan/m^3.

Legal control

In order to control land subsidence and exploit groundwater resources legally, the Tianjin local government legislated 18 laws and regulations; these laws and regulations ensured the implementation of measures against land subsidence. As early as the 1980s, Tianjin enacted "The

Interim Measures on Management of Groundwater Resources" as a basis for groundwater resource management. The problems of the exploitation of groundwater were effectively controlled. The Municipal Water Conservancy Bureau issued and implemented "The Zonation of Groundwater Exploitation Restriction," and the prohibited and restricted zones were formulated. Other local regulations, such as the "Save Water Management Regulation," "Geothermal Resources Management Rules," "Control Plan of Land Subsidence," etc., were successively developed. These laws and regulations play a significant role in land subsidence control.

Land subsidence monitoring

Accurate data are a precondition to understanding changes in land subsidence and carrying out suitable measures to prevent and mitigate disaster. Before 1985, land subsidence survey information was collected from general level surveys. The leveling survey monitoring system especially for land subsidence investigation was founded in 1985. After that time, the coverage of the monitoring area continued to increase. At present, it includes 2,100 benchmarks, 2 bedrock marks, 12 groups of multilevel layer compression monitoring wells, and 12 continuous GPS stations, covering all areas affected by land subsidence. The level monitoring line reached 5,900 km; the accuracy specification of the error of closure is within 4 mm/km (km is the length of the survey in kilometers). Figure 10 shows the locations of the bedrock benchmark points and leveling survey network. A leveling survey was conducted every year, and land subsidence information and change trends were reported in annual work reports compiled by the Tianjin Land Subsidence Control Office. The land subsidence results of this paper were summarized from all of the monitoring approaches.

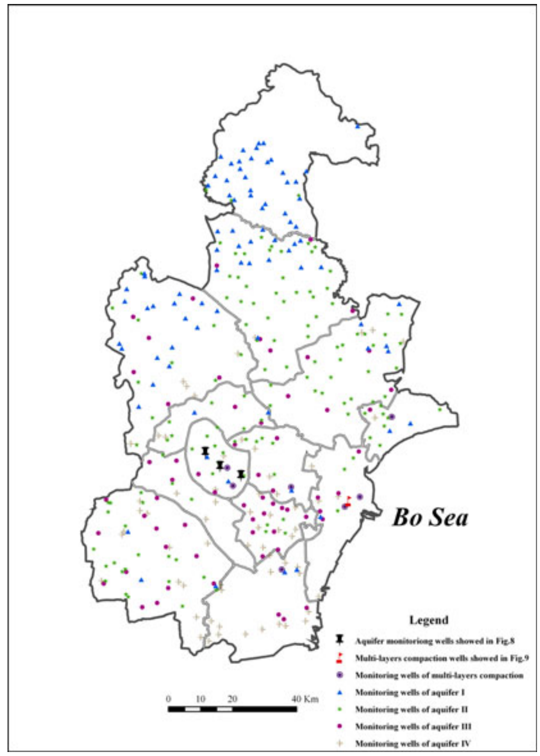

Fig. 11 The location of groundwater pressure head monitoring wells and multi-layer compression monitoring wells

Fig. 10 The distribution of benchmark points and grade I leveling survey lines

There are many groundwater head monitoring wells in Tianjin. They belong to different departments. Their locations and monitoring layers are compiled and presented in Fig. 11.

Conclusions

Land subsidence induced by overexploitation of groundwater in Tianjin in the last 50 years has been a negative consequence and created a chain of disasters in the environmental system of the area. By analyzing the development of subsidence and the effectiveness of the measures implemented to mitigate the crisis, the following conclusions can be made:

1. Overpumping of groundwater is the main cause of land subsidence in the Tianjin metropolitan area. The occurrence and the development of land subsidence are closely related to groundwater pumping both in time and space. The configuration of the subsidence cone is basically identical to the shape of the groundwater depression cone. Although groundwater extraction in the urban area has decreased, groundwater yields have continuously increased in the suburbs in recent years. As a result, land subsidence still persists, even though its rate has decreased, and the location of the most affected zone has changed.
2. The most affected areas, undergoing a subsidence rate of 30–40 mm/year, are the eastern and western suburbs. According to the regional economic development plan launched by the Chinese central government, rapid population growth in the near future along the coastal zone of the eastern suburb will create a steady increase in water demand. This would make the situation more critical in so far as water resources will not be imported. The most affected area at the peak of the crisis (the late 1970s and early 1980s) was the urban area, which experienced the highest subsidence rate of 110 mm/year. This area still continues to at 10–15 mm/year.
3. The dominant subsidence layer shifted from unit II in the 1970s and the 1980s to unit IV after the 1990s. The rebound never comes to full recovery of the ground depression because of land subsidence, even in continuously raised heads in units II and III.
4. Various measures were adopted to mitigate and prevent land subsidence disasters in Tianjin, comprising importing water resources, restricting groundwater exploitation, prohibiting use in specific zones, establishing pricing policies for water resources, advocating water-saving technology, and strictly enforcing groundwater laws. Of these measures, importing water as a substitute resource is the most effective way to control subsidence. The annual subsidence rate has been controlled, although the range of subsidence is still extending, and the cumulative subsidence is still increasing.
5. Land subsidence control is a complicated practice that involves a wide range of specialties and disciplines. The establishment of the Tianjin City Land Subsidence Joint Commission as well as its effective work in the mobilization of all sectors of society to participate in controlling land subsidence is a good example of a work pattern.
6. Restricting exploitation of groundwater in the entire area will achieve a multiplier effect in mitigating land subsidence. Eliminating the rapid development of subsidence by reducing groundwater pumping in the entire urban area within 400 km^2 is one of the greatest achievements in the process of land subsidence control.
7. Land subsidence has extensive effects in Tianjin. A chain of disasters developed in the environmental system with comprehensive negative impacts.

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