Nat Hazards (2014) 73:727–741
DOI 10.1007/s11069-014-1102-y

ORIGINAL PAPER

Overexploitation status of groundwater and induced geological hazards in China

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Received: 2 January 2014 / Accepted: 18 February 2014 / Published online: 1 March 2014

Abstract During the process of urbanization and industrialization, groundwater has been extensively overexploited, with the direct result of continuously decreasing groundwater level, followed by the appearance of large scale of depression cones, which is furthermore followed by land subsidence, seawater intrusion, and increasing difficulties in subsequent groundwater exploitation. This paper makes an analysis on the geological disasters caused by overexploitation of groundwater. The consumption and overexploitation status of groundwater in representative regions in China is discussed first, with the distribution and development of depression cones elaborated the next. And the problems of land subsidence, seawater intrusion, and increasing difficulties caused by overexploitation of groundwater are analyzed at last. Results show that overexploitation of groundwater is positively related to economic development. Moreover, geological disasters such as land subsidence and seawater intrusion caused by long term of overexploitation also aggregate, posing threats, and losses to people's lives and production. According to the analysis, the fundamental resolution for overexploitation of groundwater as well as consequential geological damages is to properly control city size and to utilize groundwater rationally and efficiently.

Keywords Groundwater · Overexploitation · Disaster · Land subsidence · Seawater intrusion

1 Introduction

As China has entered a period of rapid development, more and more groundwater resources are consumed during the process of industrialization and urbanization. Since the 1970s, groundwater has been exploited in large scale, which makes great contributions to

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China's economic development. However, problems have emerged when groundwater is overexploited and used improperly for a long period of time, throwing a threat to the sustainable development of China's water resources. More urgently, the groundwater level has been continuously decreasing due to overexploitation, which may lead to local or regional depression cones and even a series of geological disasters.

Present researches on overexploitation of groundwater in China mainly focus on the situation of the North China Plain and the Yangtze River Delta, both of which are regions with densely populated city clusters. The rapid industrial and agricultural development, coupled with underdeveloped river system, leads to massive exploitation of groundwater, which is inevitably followed by large scale of depression cones and consequential geological disasters, namely land subsidence, seawater intrusion, and deterioration of water quality as well as subsequent exploitation difficulties.

Ministry of Land and Resources of China published 15 groundwater hydrological circulars of major cities and regions from 1997 to 2011, showing the changes of evaluation indicators of various aspects, including arrangement of groundwater-monitoring sites, groundwater levels, groundwater quality, and depression cones. Lin (2004) analyzed the exploitation status of groundwater based on a comparison among the amount of groundwater, exploitable groundwater, and exploited groundwater and explored the ecological problems caused by overexploitation of groundwater. Bi (2003) made studies on regions with exploitable groundwater, discussed the amount of exploitable groundwater in each province, conducted a comparative analysis on overexploitation status of groundwater in different basins, and proposed rectifying measures. Wu (2005) described the composition of water resources in China, analyzed groundwater shortage situation, and probed into its reasons such as low efficiency of water utilization and backward irrigation technique. Gao and Gong (1999) explained the scientific meaning of overexploitation of groundwater resources, proposed new classification methods of groundwater overexploitation, and contributed suggestions to sustainable exploitation of groundwater resources.

A lot of research has been done on geological disasters caused by overexploitation of groundwater in China. Depression cones, as the by-product of groundwater exploitation, tend to expand into a large scale when the central groundwater level keeps decreasing continuously as overexploitation aggregates (Hao et al. 2009; Wang et al. 2008; Tian et al. 2011, 2012). In terms of the distribution density of depression cones, the most concentrated regions include the North China Plain region, the Yangtze River Delta region, and the Pearl River Delta region, with the North China Plain being the top of all. As for cities, Beijing (Wang 2004), Tianjin (Wei et al. 2012), Cangzhou (Zhang 2007), Langfang (Liu et al. 2008), Dezhou (Zhao 2007), and Jining (Zhou et al. 2005) located in the North China Plain, Shanghai (Gong 2009), Suzhou, Wuxi, and Changzhou (Miao et al. 2007) located in the Yangtze River Delta region, and Leizhou Peninsula (Chen 2011) located in the Pearl River Delta region are facing serious situations where expanding depression cones with large buried depth of groundwater caused by overexploitation are hindering the normal producing and domestic consumption of groundwater, especially when they are all densely populated cities with rapid development of industry and agriculture.

The nature of depression cones is uneven lowering of groundwater level. Groundwater level lowering will lead to soil consolidation, and when soil consolidation develops to a certain extent, over subsidence occurs which will cause damages to buildings and underground pipelines. Wang (2004) analyzed the relationship between overexploitation of groundwater and the scope, extent and rate of land subsidence in Beijing. Results indicate a high consistency in time and space among regions with severe overexploitation of groundwater, the central places of depression cones, and areas of land subsidence. Miao et al. (2007) studied the relationships between the exploitation status of confined water and land subsidence in regions of Suzhou, Changzhou, and Wuxi. Xue (2012) probed into the characteristics of land subsidence caused by overexploitation of groundwater in China and proposed suggestions based on deposition modeling. Jiang et al. (1999) made a study of land subsidence caused by exploitation of karst groundwater in Xuzhou, Xi'an, Taiyuan, and Qinhuangdao.

Another major geological disaster caused by overexploitation of groundwater is seawater intrusion. Guo and Huang (2003) summarized the history of seawater intrusion, clarified the concept of seawater intrusion, and concluded its evaluation indicators and detection methods. Miao et al. (2013) analyzed the development and characteristics of seawater intrusion in Laizhou Bay, the most seriously affected area in China. Huang and Guo (2008) studied the geochemical process and geological environment impact of seawater intrusion and elaborated on the relationships between exploitation volume of groundwater and seawater intrusion with Longkou as an example. Liu (2004) made an analysis on the mechanism, causative factors as well as damages to seawater intrusion, demonstrated the hazards of overexploitation of groundwater, and proposed rectifying measures including reducing exploitation volume and recharging.

2 Overexploitation status in China

Statistics (Lin 2004) show that there are altogether 164 overexploitation zones in China, with the total area amounting to 181,300 km^2, among which the severely overexploited area is 77,000 km^2, taking up 42.5 % of the total area. According to dynamic monitoring of shallow groundwater exploitation zones with a total area of 750,000 km^2 in 17 provinces in North China, the storage of shallow groundwater decreased by 15.1 billion m^3 in 2002 compared with 2001, with the descending area amounting to 69 % of the total region. From 1994 to 2002, the storage of groundwater in North China Plain had been decreasing all the way with the exception of year 1994 and 1998 only. The maximum decreases happened in 1997 and 2001, with the reduction of 17 billion m^3 and 20 billion m^3, respectively. Up to 2002, the cumulative reduction in groundwater storage reached 60 billion m^3 compared with 1994, while Hebei Province topped the others with a total reduction of 16 billion m^3 alone.

The North China Plain is severely bothered by the problem of overexploitation of groundwater. As one of the most densely populated regions in China, the North China Plain is in huge demand of water resources to satisfy urban and agricultural utilization. However, the river system in northern China is underdeveloped, which inevitably leads to the result of large-scale exploitation of groundwater. The exploitation data from 2005 to 2009 is shown in Table 1 (The Ministry of Water Resources of China 2005, 2006, 2007, 2008, 2009). It can be seen that the exploitation amount is large and kept at a high level. In 2009, the exploitation amount reached 72.56 billion m^3 after a sharp increase from 67.09 billion m^3 in 2008.

China is now in the process of industrial and agricultural transformation, large demand for water resources coupled with immature water-saving technology lead to the fact that industrial and agricultural water consumption takes up a large share for a long period of time. Take 2003 for example, an increase of every 10,000 dollars in GDP in China consumed 3,860 m^3 water, which is four times the global average and 5–10 times the average of developed countries (Wu 2005). On the other hand, domestic water

Table 1 Exploitation amount of groundwater in the North China Plain (billion m^3)

Year	2005	2006	2007	2008	2009
Total exploitation amount	68.4	69.4	65.66	67.09	72.56
Shallow groundwater exploitation amount	58.5	58.81	54.18	54.9	60.96
Confined water exploitation amount	9.9	10.59	11.48	12.19	11.6

Table 2 National water consumption (billion m^3)

Year	Domestic	Industrial	Agricultural	Ecological	Total amount
2007	71.04	140.41	359.85	10.57	581.87
2008	72.92	139.71	366.34	12.02	590.99
2009	74.82	139.09	372.31	10.30	596.52
2010	76.58	144.73	368.91	11.98	602.20
2011	78.9.9	146.18	374.36	11.19	610.72

Table 3 Overexploitation status of different river basins in China

River basin area	Overexploitation (km^2)	Severe overexploitation (km^2)	Annual overexploitation amount (billion m^3)
Songhuajiang River and Liaohe River	12,521	9,746	0.700
Haihe River	89,068	39,680	3.911
Huanghe River	19,245	9,433	1.031
Huaihe River	23,605	9,089	0.639
Changjiang River	11,905	1,369	0.356
Zhujiang River	1,027	631	0.082
Inland Rivers	23,951	3,401	0.410

consumption is also extraordinary and the reason is lack of water-saving consciences and water-saving technology.

National water consumption status in China is shown in Table 2 (The Ministry of Water Resources of China 2007, 2008, 2009, 2010, 2011). It can be seen that domestic water consumption continues to show an upward tendency. Industrial and agricultural water consumption remains at a high level, which also shows an upward trend. Water used for ecological development essentially unchanged, while the total consumption is continuing to increase from 581.87 billion m^3 in 2007 to 610.72 billion m^3 in 2011. It can be deducted that huge water consumption is the direct reason for large-scale exploitation of groundwater, while reducing water consumption is a fundamental measure to protect groundwater resources.

Because of various reasons, the groundwater exploitation amount keeps exceeding recharge amount, followed by overexploitation in many regions nationwide. Overexploitation situation of different river basins is shown in Table 3 (Bi 2003).

The most distinctive feature of overexploitation of deep groundwater is continuous declining of groundwater level, which leads to an increasing depth of exploitation wells. For example, in Dezhou city, the deep groundwater level has been declining ever since

1965 as overexploitation continues, with an average decrease of 30–35 m from 1965 to 2009. The maximum decrease in water level in downtown area of Dezhou is above 100 m, with the number reaching 134.14 m at central exploitation point. From 1978 to 2009, the decrease is about 100 m, while the number in the center of depression cone has reached 133.90 m, top of the whole North China Plain (Yang et al. 2010).

3 Depression cones caused by overexploitation

As water consumption increases, more and more underground pumping wells are dug, leading to continuous emerging of depression cones with their range enlarging and central water level declining continuously. In major cities, the area and depth of depression cones usually develop fast because of large population, developed industry, and agriculture. Consequently, the geological hazards caused by depression cones are more severe than other places.

As for Beijing, since the 1960s, the exploitation of groundwater has seen a rapid growth with an annual overexploitation amount of 0.1 billion m^3. Up to 2000, the cumulative loss of water resources reached 5,710.4 billion m^3 in the plain area.

The area of depression cones in urban and suburban regions of Beijing reached 152 km^2 in 1959. The number was 718 km^2 in 1975. The exploitation of groundwater saw a dramatic increase from 1980 to 1984 due to drought in 5 consecutive years. Up to 1986, the depression cones in urban and near suburb regions joined into a mass zone with the total area reaching 1,155 km^2 and the groundwater level decreasing by 20–36 m from 1959. The drought and overexploitation circle repeated itself from 1999 to 2001, with the total area of depression cones reaching 1,900 km^2 in 2004 (Wang 2004). Figure 1 presents the development of depression cones area from 1975 to 2001 (Ren 2005). It can be seen from Fig. 1 that the area of depression cones has enlarged dramatically, indicating that the status of overexploitation of groundwater was getting worse gradually along with the development of urbanization.

Dezhou city, another major city in North China, is one of the cities with extensive exploitation of groundwater. The exploitation of deep groundwater in Dezhou began in 1965, while the first depression cone appeared in 1970. In 1973, the number of deep wells was 33, the exploitation amount was 8.25 million m^3/a, the buried depth of groundwater in the depression cones center was 30.0 m, and the total area of depression cone was 37 km^2. Up to 1990, the number of deep wells was 158, the exploitation amount was 19.07 million m^3/a, the buried depth of groundwater in the depression cones center was 76.23 m, and the total area of depression cones was 1,707.5 km^2. Up to 2010, the number of deep wells has reached 278, while the exploitation amount is 33.54 million m^3/a. Among the 278 deep wells, 174 is of the depth of 300–500 m and an exploitation amount of 19.89 million m^3/a; 104 is of the depth of 500–900 m and an exploitation amount of 13.66 million m^3/a. The total area of depression cones amounts to 31,939.8 km^2 (Yang et al. 2010).

Daqing city, located in the Northeast China, also faces the severe pressure of overexploitation. Decrease in groundwater level in Daqing began in 1963. In 1972, the exploitation amount was 0.055 billion m^3, the buried depth of groundwater was 20.90 m, the groundwater level decreased by 9–14 m, and that was when the depression cone appeared. After 1972, the exploitation amount increased constantly and reached 0.114 billion m^3 in 1976, while the buried depth of groundwater in the depression cones center reached 29.70 m. The depression cones had been developing fast during this period with its total area enlarging to 2,500 km^2 and groundwater level decreasing by 9.88 m. The exploitation

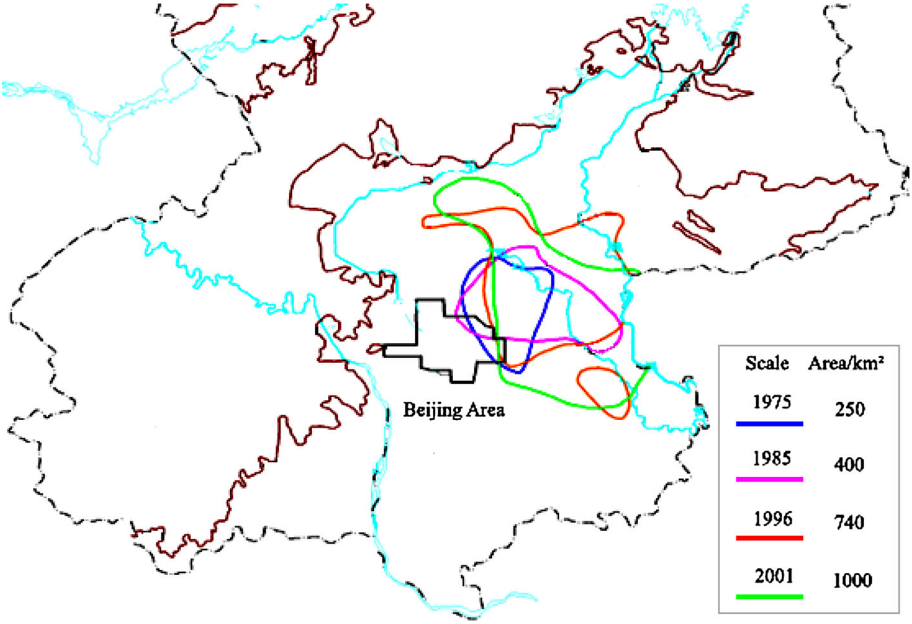


Fig. 1 The development of depression cones in the plain area of Beijing

amount continued to increase after 1976 and reached 0.2 billion m^3 in 1986, while the buried depth of groundwater in the depression cones center was 35.54 m. Up to 1992, the exploitation amount was 0.24 billion m^3, the buried depth of groundwater reached 36.90 m, and the cumulative decrease was about 30 m. In 1993, the exploitation amount was 0.305 billion m^3, while the area of depression cones extended to 4,500 km^2. In 1997, the exploitation saw a little fall back with the amount of 0.219 billion m^3, and the area of depression cones was 4,000 km^2. In 2001, the exploitation amount was 0.281 billion m^3, while the central groundwater level declined to 41.70 m, followed by a stable tendency and even a slight increment (Tian et al. 2011).

According to the analysis of the three cities mentioned above, overexploitation of groundwater induces the appearance of depression cones in large scale. The exploitation amount and the area of depression cones as well as the decrease in central groundwater level are positively related.

Figures 2, 3, 4, 5, 6, 7, 8, and 9 show the distribution of depression cones in shallow groundwater and deep groundwater from 2008 to 2011 (The Ministry of Land and Resources of China 2009, 2010, 2011, 2012). It can be seen that the North China Plain, the Yangtze Delta, and the Pearl River Delta fall into the concentrated regions. For those regions, strict measures should be taken to control water exploitation and prevent city geological disasters.

4 Land subsidence caused by overexploitation

Large scale of depression cones, together with continuous decreasing groundwater level in certain regions, will lead to a series of geological disasters, among which land subsidence resulted from the changes of the soil stress state is the most urgent problem. Land

Fig. 2 2008 depression cones in shallow groundwater

Fig. 3 2008 depression cones in deep groundwater

subsidence will cause great economic loss and even casualties especially when it happens in urban area causing damage to buildings, underground pipelines, and pavement break joint. Up to the end of 2007, the total loss caused by land subsidence in the North China Plain reached 332.828 billion RMB, among which the direct loss was 40.442 billion RMB and indirect loss was 292.386 billion RMB (He et al. 2009).

Fig. 4 2009 depression cones in shallow groundwater

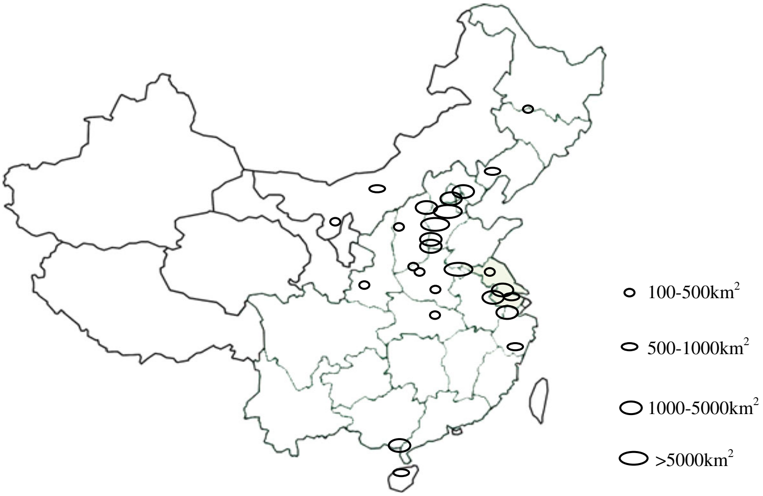


Fig. 5 2009 depression cones in deep groundwater

During the dewatering process in phreatic stratum, the effective stress of soil changes as the pore water pressure dissipates. Figure 10 illustrates the calculation procedure of dewatering in phreatic stratum.

When groundwater level decreases from the original water table by the depth of h, the change of pore water pressure at point A is

$$\Delta u = -\gamma_{\mathrm{w}} h,$$

the change of effective pressure is

$$\Delta \sigma' = \gamma h - \gamma' h,$$

Fig. 6 2010 depression cones in shallow groundwater

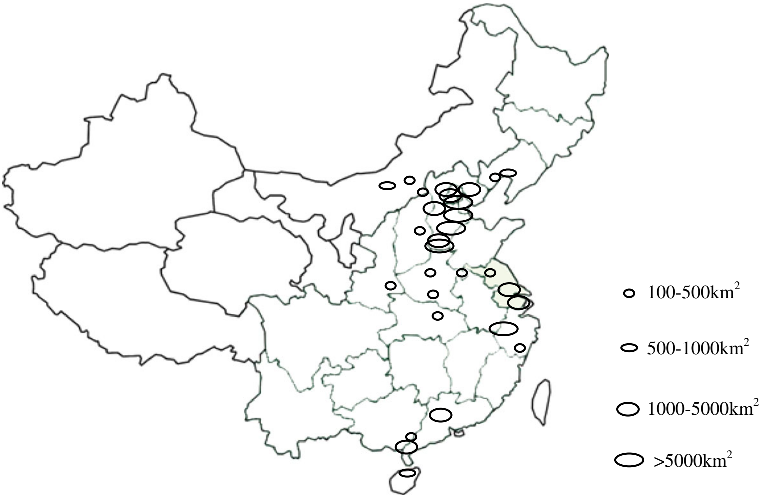


Fig. 7 2010 depression cones in deep groundwater

the change of total pressure is

$$\Delta\sigma = \Delta u + \Delta\sigma' = (\gamma - \gamma' - \gamma_{\mathrm{w}})h.$$

In the above equation, γ_{w} represents the weight of water, γ represents the wet weight, and γ' represents the floating weight.

Thus, to get the subsidence of dewatering belt

$$S = h \cdot \Delta\sigma'/E_{\mathrm{s}},$$

In this equation, E_{s} is the deformation modulus, and S is subsidence value.

Fig. 8 2011 depression cones in shallow groundwater

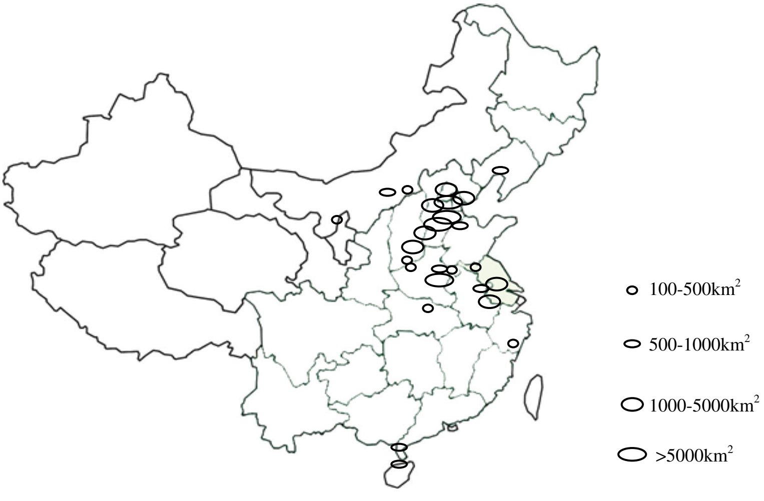
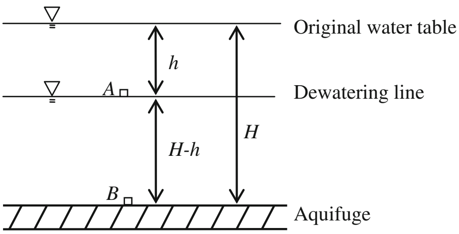


Fig. 9 2011 depression cones in deep groundwater

Fig. 10 Phreatic stratum dewatering calculation diagram



For a certain point B below the dewatering line, the change of effective pressure is

$$\Delta\sigma' = \gamma h - \gamma' h.$$

Thus, to have the subsidence between the dewatering line and the aquifuge,

$$S = (H - h) \cdot \Delta\sigma' / E_{\mathrm{s}}.$$

Based on the above analysis, the total subsidence of phreatic stratum is

$$S = hH(\gamma - \gamma')/E_{\mathrm{s}}.$$

According to Terzaghi one-dimensional consolidation theory, the total pressure of soil in the confined aquifer remains unchanged during the dewatering process, so the increased value of effective pressure equals to the decreased value of pore water pressure. Thus, to have the subsidence of confined aquifer after dewatering

$$S = H \cdot \Delta\sigma' / E_{\mathrm{s}} = H \cdot \gamma_{\mathrm{w}} z / E_{\mathrm{s}}.$$

In the equation, z represents the change of confined aquifer water head, and H represents the depth of confined aquifer.

It can be seen from theoretical analysis that depression cones will severely affect land subsidence, because the equations derived above show that the larger the drawdown of groundwater, the lager land subsidence will happen. Therefore, the extending of depression cones as well as the decrease in groundwater level will end in dramatic land subsidence in large scale. Take Jining city in the North China Plain, for example (Zhou et al. 2005), land subsidence deteriorated when the exploitation amount of groundwater reached 96.71 billion m^3/a in 1994. From August 1992 to May 2000, land subsidence in the northwest area of the city and area along the National Highway No. 327 was more than 100 mm, with the maximum value reaching 188.6 mm.

In Dezhou city (Yang et al. 2010), land subsidence was comparatively slighter when the buried depth of deep groundwater was <80 m before 1991. From 1991 to 2000, the buried depth of deep groundwater saw a dramatic increase from 79 to 111 m, while land subsidence began to aggregate with subsidence value in the center of the depression cones being 517 mm. From 2000 to 2005, the buried depth of deep groundwater increased from 111 to 130 m, while land subsidence aggregated quickly with subsidence value in the center of the depression cones being 936 mm. From 2005 to 2006, the decrease in central groundwater level of depression cones slowed down, and land subsidence also slowed down with annual subsidence value decreasing to 56 mm. Results show a synchronization between land subsidence and decrease in deep groundwater in depression cone area, indicating the major influence of the latter on the former.

Land subsidence is not exclusive to North China. In South China, land subsidence also aggregates as the groundwater level declines. Land subsidence status in Suzhou and Changzhou in the Yangtze River basin is shown in Figs. 11 and 12 (Miao et al. 2007).

It can be obtained from Figs. 11 and 12 that land subsidence values are positively related to groundwater level values. In Fig. 11, groundwater level gradually declined from −32.5 m in 1984 to −47 m in 1997, while land subsidence value decreased from 0 mm in 1984 to −230 mm in 1997. After 1997, the groundwater level showed a recovery trend, which leads to a slowdown of the subsidence velocity. The relationship between groundwater level and subsidence in Fig. 12 is similar to that in Fig. 11. From 1969 to 1994, the groundwater level declined from −25 to −81 m. At the same time, the value of land subsidence gradually reached the minimum value of about −50 mm. After that, the

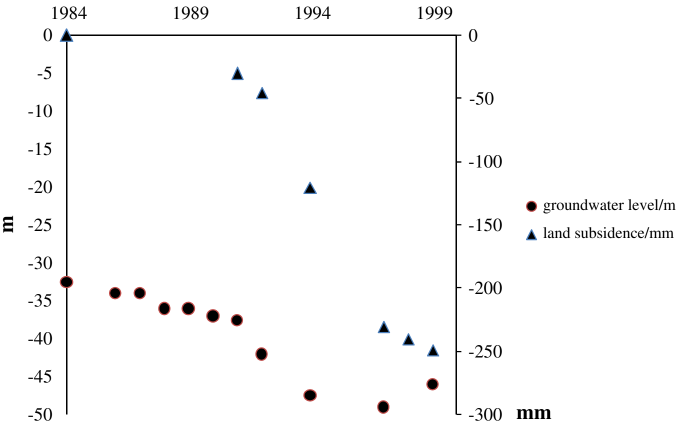


Fig. 11 Relationship between groundwater level and land subsidence at Guoxiang, Suzhou

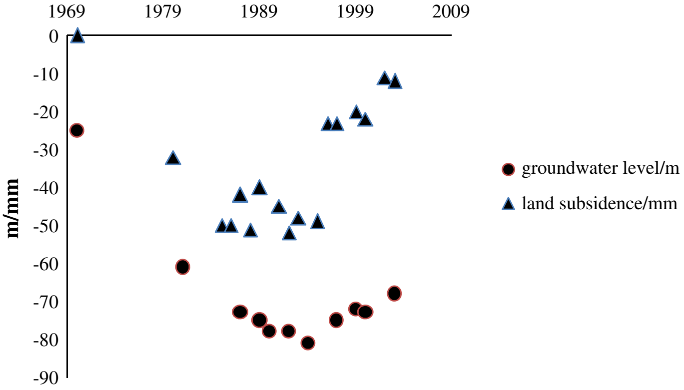


Fig. 12 Relationship between groundwater level and land subsidence at Qingliang Primary School, Changzhou

land subsidence value went up from −50 to −11 mm as the groundwater level rose from −81 to −68 mm.

5 Seawater intrusion caused by overexploitation

In China, the first case of seawater intrusion happened in Dalian in 1964. In the late 1970s, another case was found in Laizhou Bay. In the 1980s, seawater intrusion accelerated with expanded scope and damage. Up to 2003, seawater intrusion had been found in most coastal regions, namely Huludao, Dalian, Qinhuangdao, Tianjin, Shandong Peninsula, Northern Jiangsu Plain, Shanghai, Ningbo, and Beihai, of which Laizhou Bay of Shandong Peninsula was the most serious (Guo and Huang 2003) and the intrusion area has become salinization (Zhou and Zhao 2013). By the end of 1995, the area of seawater intrusion of Laizhou Bay reached 974.6 km^2. According to incomplete statistics, there were 400,000 people facing drinking water problems, more than 8,000 agricultural wells scrapped, more than 400 km^2 of farmland lost irrigating capacity with an annual grain reduction of 300 million kg, and an annual industrial loss of 400 million RMB (Guo and Huang 2003).

By 2007, seawater intrusion mainly occurred in Shandong and Hebei provinces. The cumulative area of seawater intrusion in Dongying, Weifang, Qingdao, Weihai, Rizhao, and Yantai et al. of Shandong Province has reached 3,441.8 km^2. The cumulative area of seawater intrusion in Qinhuangdao et al. of Hebei Province reached 340.8 km^2 (Ministry of Land and Resources of China 2008). Seawater intrusion area in Northern Liaodong Bay and its coastal regions has been more than 4,000 km^2, of which the serious intrusion area is 1,500 km^2. In Laizhou Bay, the area of seawater intrusion has reached 2,500 km^2, including the serious intrusion area of 1,000 km^2. The maximum intrusion distance of south Laizhou Bay was 45 km.

In the southern coastal of China, seawater intrusion distance has reached 1.5 km with serious intrusion distance of 0.7 km in Changle, Fujian Province. In Putian, coastal seawater intrusion zone stretched to approximately 4.0 km, of which serious intrusion reached 3.0 km. In Beihai, Guangxi Province, serious seawater intrusion zone stretched to approximately 0.3 km. The serious seawater intrusion in Sanya, Hainan Province has reached 0.25 km (State Oceanic Administration of China 2007).

It can be seen from the data above that seawater intrusion is serious in both North and South China. If overexploitation status gets worse, seawater intrusion will cause more damage to the groundwater resource.

6 Increasing difficulty in groundwater exploitation

The formation and development of depression cones causes increasing difficulties and cost of groundwater exploitation, with deeper wells, higher drilling cost, more frequently updates of pumps, more scrapped wells, and less water yield. For example, at Fenghuadian Village of Cangzhou city, the water could not be pumped into the farmland for irrigation due to low water level in May and June since 2003. Additional pumps had to be installed at the wellhead, which greatly increased the irrigation cost to six or even eight times of that in 1980s. Up to now, the deep well pumps have been renovated for four generations, while the depth of wells increasing to 180–220 m from 100 m in early 1980s (Zhang 2007).

7 Conclusions

Status of overexploitation of groundwater in China is serious, which throws severe impediments to the ecological cycle of groundwater. It can be seen from this paper that overexploitation of groundwater caused dramatic decline of the water table in the North China Plain, the Yangtze River Delta, and Pearl River Delta region, forming huge areas of depression cones. Meanwhile, with the urban development and the increase in population, areas of depression cones are increasing and the center water levels continue to decline, which lead to geological hazards of land subsidence, seawater intrusion, and increasing difficulties in groundwater exploitation, etc., causing enormous economic losses or even threats to people's lives.

In order to reduce the harm of overexploitation of groundwater, various measures should be taken, such as rational use of water, proper control of the city and the population size, developing water-saving technologies, and improving people's awareness of water conservation. Only by reducing the consumption of groundwater fundamentally can geological disasters caused by overexploitation be avoided.

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