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Groundwater resources protection and management in China

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Abstract

Groundwater is an important water source to support China's economic and social development. Since the 1970s, China, especially the north region, has started to intensively pump groundwater as a water supply for agricultural irrigation, industry and city expansion. To meet the water demand due to the rapid development of the economy and society, groundwater is continuously and disorderly exploited to a great extent for a prolonged time in some regions in China, besides faulty operation and management, and insufficient emphasis on protection, which leads to severe problems of groundwater over-exploitation and contamination. In recent years, the Chinese government has attached great importance to groundwater protection. This paper illustrates the general ideas and strategies of groundwater protection and management in China from the aspects of over-exploitation control, quality protection, water ecosystem protection, and implementation of the strictest water management systems.

Keywords: China; Groundwater protection; Over-exploitation; Pollution

Introduction

In China, groundwater is a vital support for human living, economic and social development, and is especially irreplaceable, particularly in dry years or in emergencies, so it is important to minimize loss from disasters and maintain social stability. In addition, groundwater plays a key role in maintaining ground vegetation, adjusting river runoff, and protecting the ecological environment during the course of its formation, conversion, and migration. The characteristics of groundwater resources differ greatly in different regions in China. In addition, the situation and level of water demands vary greatly by regions, influenced by demographics, economy and ecology.

Since the 1980s, groundwater has been overly developed and utilized to cater for economic and social growth in some regions, where the serious over-exploitation of groundwater has resulted in environmental and geological problems such as land subsidence and collapse, declined water table, spring

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dry-up, seawater intrusion, shrinkage of wetlands and water pollution (Wang *et al.*, 2013). Therefore, groundwater has become a key constraint of economic and social sustainability in China.

In recent years, the Chinese government has attached great importance to groundwater protection, and has announced a series of documents with clear instructions (e.g. 'Decision of the State Council on Accelerating the Reform and Development of Water Conservancy' in 2011; 'Opinions of the State Council on the implementation of the most stringent water resources management system' in 2012; 'Decision of the CPC Central Committee on Deepening the Reform of Several Major Issues' in 2013; etc.).

Availability and distribution

The annual average amount of groundwater resources (TDS (total dissolved solids) is less than or equal to 2 g/L) from 1980 to 2000 is 818.8 billion m^3/a. The annual average amounts of groundwater in the plain and mountainous areas are 176.5 and 677.0 billion m^3, respectively, with 31.7 billion m^3 counted in duplicate.

The annual average sustainable yield of groundwater in the plain areas means that the largest amount of groundwater, evaluated at 1,230 m^3/a, accounts for 70% of the annual average amount of groundwater resources in these areas and can be extracted from aquifers without causing ecological and environmental problems.

Figure 1 shows a comparison between groundwater amounts in the south and the north. Thirty percent of total groundwater is in the north. However, since more plain areas are distributed in the north in China, 78% of groundwater in plains is in the north, and 81% of sustainable exploitation amount in the plains is in the north.

Changes in the north

According to the 'National Water Resources Bulletin', the annual average amount of groundwater resources from 2001 to 2015 was 253 billion m^3/a, which is an increase of 3.1% compared to the average amount from 1980 to 2000.

Six major basins are included in the north, namely Songhua River basin, Liaohe River basin, Haihe River basin, Yellow River basin, Huaihe River basin and the Northwestern Rivers basin. Four major river basins are included in the south, namely Yangtze River basin, Pearl River basin, Southwestern Rivers basin and the Southeastern Rivers basin (Yang *et al.*, 2014). Table 1 shows a comparison of

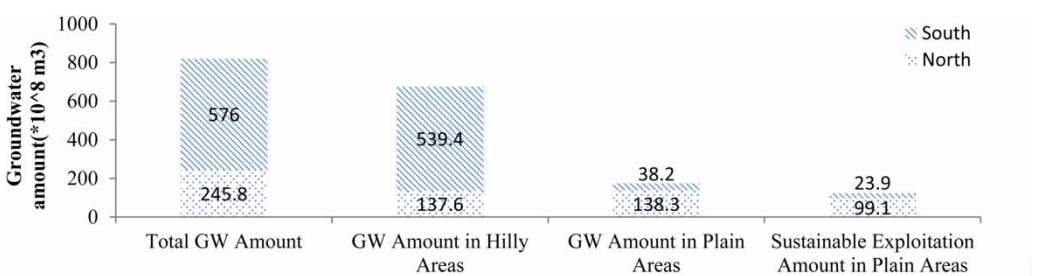

Fig. 1. Comparison of groundwater resources (GW) amount in the south and the north.

Table 1. Comparison of groundwater resources amount of six northern basins between 1980–2000 and 2001–2012.

River basins	Annual average amount for 1980–2000 (10^8 m^3)	Annual average amount for 2001–2012 (10^8 m^3)	Comparison
Songhua River	478	447	−6.50%
Liaohe River	203	179	−11.80%
Haihe River	235	221	−6.00%
Yellow River	376	380	1.10%
Huaihe River	397	418	5.30%
Northwestern Rivers	770	889	15.50%
Total	2,459	2,534	3.10%

the annual average amount of groundwater in six basins for 1980–2000 and 2001–2012. The annual average amount of groundwater resources for the Songhua River, Liaohe River and Haihe River decreased by more than 6%, due to less precipitation and intensive exploitation. Nevertheless, the values for the Yellow River, Huaihe River and Northwestern Rivers increased, especially for the Northwestern Rivers, and the amount increased by 15.5% due to more precipitation and snow melting from the mountains.

Groundwater supply

Groundwater exploitation had increased dramatically from 1972 to 2000, with an annual average increase rate of 4.4%. Since 2000, groundwater use for the whole country has been relatively stable, with the amount being around 110 billion m^3/a. The nationwide groundwater use in 2013 was 113 billion m^3/a, accounting for 18% of the nationwide total water supply. Figure 2 shows the nationwide groundwater use changes from 1972 to 2013.

Most groundwater utilization in China occurs in the north (Yang *et al.*, 2014). In 2013, groundwater exploitation for the six river basins in the north was 100 billion m^3/a, accounting for 89% of the whole country's amount, and nearly 36% of the total water supply in the basins. For Haihe River basin, more than 60% of the water supply is from groundwater resources. Figure 3 shows the percentage of groundwater exploitation in the total water supply for 10 river basins.

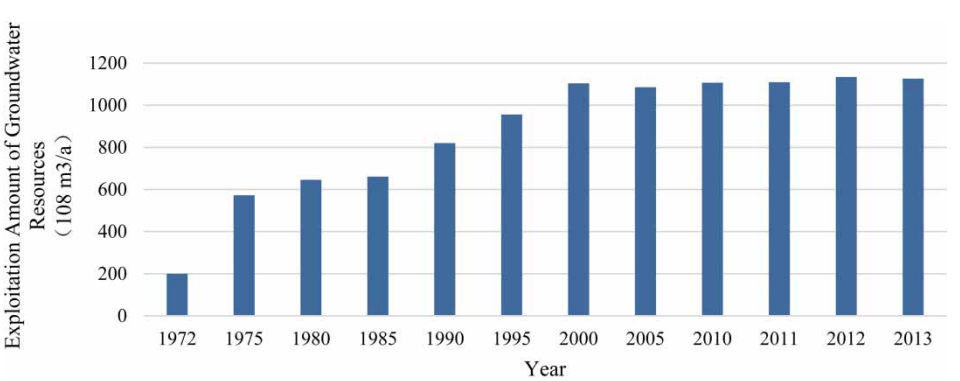

Fig. 2. Nationwide groundwater use changes from 1972 to 2013.

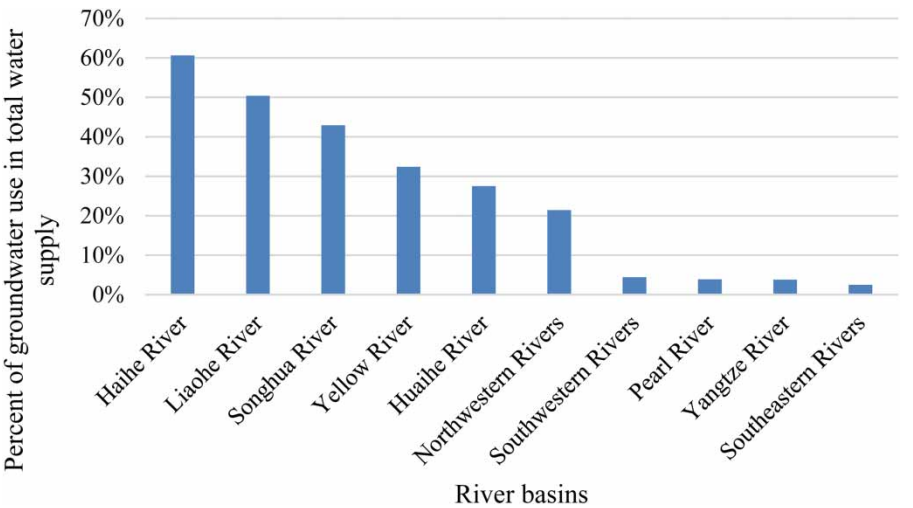

Fig. 3. Percentage of groundwater exploitation in the total water supply for 10 river basins.

The average intensity of groundwater exploitation in the plain areas (the ratio of the amount of groundwater exploitation to the sustainable yield) of the north region is more than 85%, and even more than 100% in the plain areas of Hebei, Tianjin, Henan, and Shanxi provinces. Figure 4 shows the intensity of groundwater exploitation in the plain areas of each province. The horizontal line indicates the national average, which is around 72%.

Agriculture consumes most groundwater, however, its shares in the total groundwater use have declined in the past 30 years, from 88% in the 1980s to 65% in 2012. Figure 5 shows China's groundwater use by sectors.

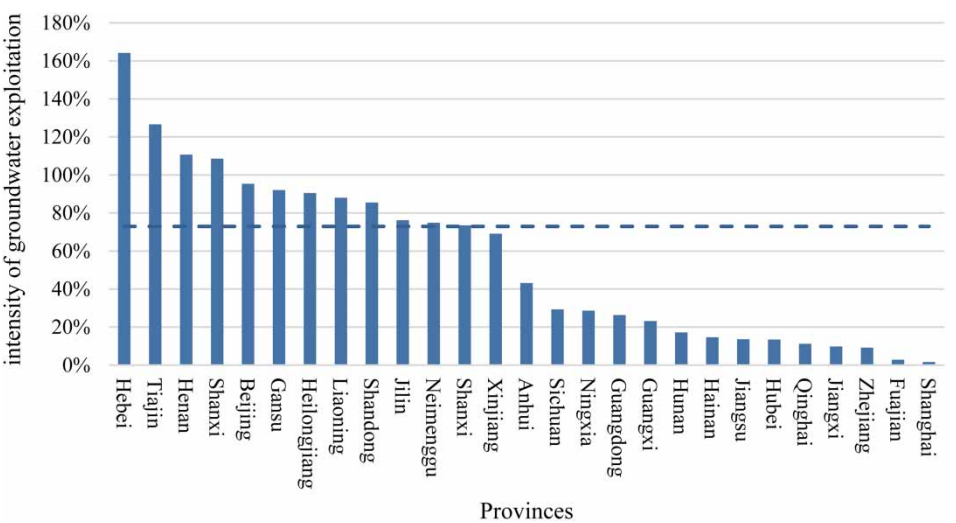

Fig. 4. Intensity of groundwater exploitation in the plain areas.

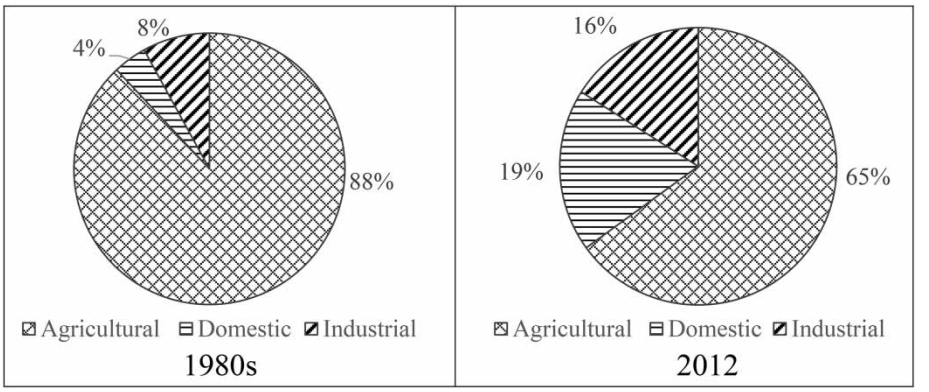

Fig. 5. Groundwater uses by sectors.

Issues

Over-exploitation in four basins

It has been investigated that the over-exploitation area in the plains is almost 300,000 km^2, in which the area with shallow groundwater is 152,000 km^2 and the area with deep confined water is 161,000 km^2 with an overlapping area of about 18,000 km^2.

Most of the groundwater over-exploitation areas are distributed in northern China, and 88% are in the four river basins, including Haihe River basin, Huaihe River basin, Yellow River basin and Northwestern Rivers basin (Wang *et al.*, 2000). The over-exploitation areas and water amounts of these four basins can be seen in Figure 6.

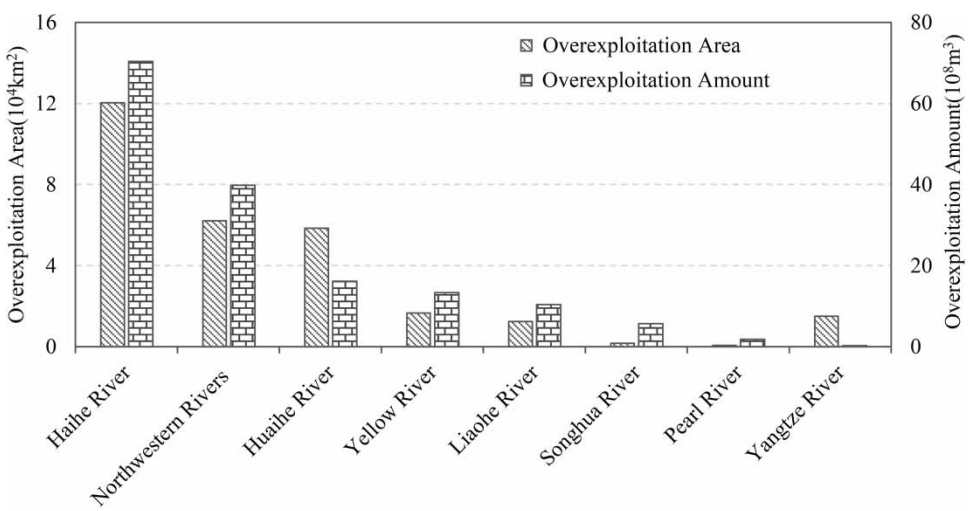

Fig. 6. Groundwater over-exploitation amount and area of eight river basins. (*Note:* no groundwater over-exploitation problems in the basins of Southwestern Rivers and Southeastern Rivers.)

Serious problems caused by groundwater over-exploitation

Depletion of groundwater resources. Due to continuous over-exploitation over a long period of time, groundwater levels kept declining in some regions with aquifers depleted and storage volume decreased greatly, which causes serious damage to the aquifer or the loss of emergency reserves function of the groundwater (Yang *et al.*, 2012).

It was estimated that as at the end of 2013, the accumulated loss of groundwater reserves in the northern plain areas was more than 250 billion m^3 compared with that in 1980. See Figure 7 for the estimation of accumulated loss of groundwater reserves in the northern plain areas in 1980–2013.

Land subsidence. The area of the regions with an accumulated ground settlement of over 200 mm has been up to 79,000 km^2 in China, in which the North China Plain, the region with the largest distribution of continuous ground settlement in China, accounted for 62,000 km^2 and the Yangtze River Delta accounted for 10,000 km^2. There are over 50 cities with ground settlement, distributed in over 20 provinces and regions (Xue, 2012).

Seawater (saltwater) intrusion. According to some statistics, as at 2010, the area of seawater intrusion in the coastal region caused by groundwater over-exploitation was about 2,500 km^2; the coastal region is mainly distributed in the coastal Bohai and Huanghai sea. In some other places, such as the local areas of Hebei and Shandong provinces in the North China Plain, a saline water layer exists in the shallow aquifer, and the groundwater exploitation area thus refers to aquifer below the saline layer. Due to the long-term massive exploitation, the groundwater level declined continuously and caused the intrusion of upper salt water into the freshwater aquifer. The area of total salt water intrusion in China is over 1,000 km^2, mainly distributed in Hebei and Shandon provinces.

Land desertification. Due to groundwater over-exploitation or subsequent decreasing of surface water, the groundwater level kept decreasing in some arid and semi-arid areas, which resulted in regional vegetation degradation and desertification acceleration. There is land desertification to different extents in Bashang region in Hebei, Tongliao in Inner Mongolia, Shiyang River along Hexi Corridor of Gansu, and other regions.

Spring attenuation. In the past 30 years, human activities have influenced groundwater resources directly or indirectly and even broken the discharge and recharge balance of the groundwater resources

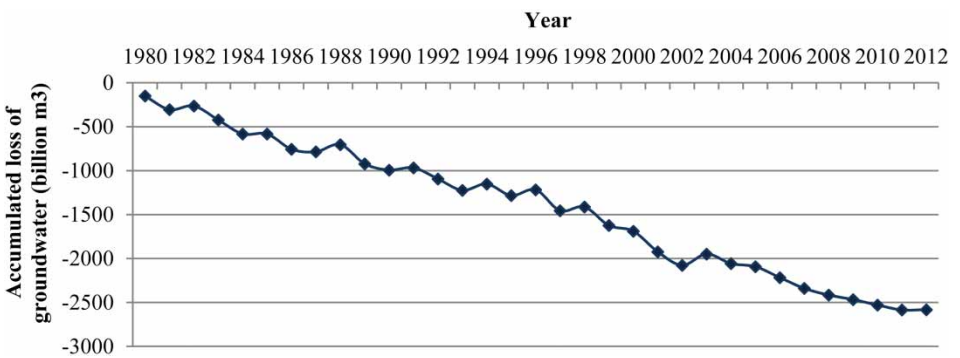

Fig. 7. Estimation of accumulated loss of groundwater reserves in the northern plains.

of some regions, which has resulted in the decreasing of groundwater level and spring flow, even the drying up of springs. The current average spring flow decreased by over 50% from that in the 1950s in Niangziguan Spring, Shentou Spring, Pingshang Spring and Xin'an Spring in Shanxi, Heilongdong Spring, Baiquan Spring, Yimuquan Spring and Weizhou Spring in Hebei, Pearl Spring in He'nan, and other well-known springs. Some springs have even dried up.

Quality and pollution

Groundwater resources are facing severe issues of pollution in some regions. First, some industrial activities pollute the groundwater environment. Unsealed or poorly waterproofed industrial storage areas or yards for slag, raw materials, products or waste from mines, chemical or petrochemical industries, as well as fuel refilling stations, often leak, polluting the groundwater with chemicals (Zhu & Xu, 2009). Second, the excessive tonnage of fertilizers and pesticides used in agricultural activities also pollutes the groundwater by percolating into the ground during irrigation or rain events. Third, in some coastal areas, especially in the northeastern provinces, the over-exploitation of groundwater leads to seawater intrusion into the near-shore groundwater aquifer that cannot be reversed.

According to the 'Investigation and Assessment of China's Water Resources and Utilization', in more than 26% of plains in China, groundwater quality has been affected by human pollution to different extents. The heavily polluted areas are mainly distributed in the central metropolitan areas, peripheral urban areas, alongside the drainage rivers, surface-water-contaminated areas, as well as farmland irrigated by polluted water. About half of the urban groundwater is severely polluted, and the groundwater quality of most cities tends to deteriorate. Shallow groundwater for several cities is not qualified for direct drinking, which all makes the number of water-lacking cities and regions increase rapidly (Tang *et al.*, 2006).

Objectives of groundwater protection in China

Goals

The overall goal of China's groundwater management and protection is to reasonably adjust its development and utilization pattern, to control groundwater over-exploitation, to reach the balance of exploitation and sustainable yield, to change the decreasing trend of groundwater levels, and to achieve sustainable use of groundwater.

By 2020, groundwater exploitation throughout the country should be limited to 100 billion m^3 per year. Excessive exploitation should be strictly prohibited and progressively reduced, in particular in north China, to limit use to a sustainable yield. The quality and safety of important groundwater sources used for drinking water should be basically secured and protected. A national groundwater monitoring management information system should be preliminarily established.

By 2030, groundwater exploitation throughout the country should be limited further to around 93 billion m^3 per year. Groundwater overdraft areas should be basically eliminated to allow a reasonable balance between recharge and abstraction. The national groundwater monitoring management information system should be expanded and improved.

Regional deployment

Different groundwater conditions and exploitation variations in different regions should be focused on; especially, some areas have severe over-exploitation issues while others need alternative water

sources to guarantee economic and social development. In order to achieve reasonable exploitation and utilization of groundwater with fewer problems and more supportive functions for development, it is necessary to adjust the layout of groundwater withdrawal.

First, the groundwater exploitation in overdraft regions should be largely reduced to allowable withdrawal ranges to treat the overdraft problem and restore the damaged eco-environment, and the most prominent example is the North China Plain.

Second, some areas with relatively high development intensity but fewer overdraft problems are planned in the water-receiving regions of several water diversion projects and more surface water will be available when the water diversion projects are built in the future. Aiming at maintaining more groundwater reserves, less groundwater can be exploited in these areas.

Third, some areas with fragile eco-environments are highly dependent on groundwater, as in the northwest of China where the precipitation is scarce and the groundwater level is the key element of maintaining plant growth and wetland areas. The groundwater exploitation in these areas should be strictly controlled and appropriately reduced on the current basis.

Fourth, in some areas with low utilization of groundwater, groundwater withdrawal could be appropriately increased to ensure water use, and these areas are mainly located in the south. Especially in the mountainous areas, increasing the groundwater draft would benefit the farmers' domestic demands and future economic development.

Major measures for groundwater management and protection

To realize the goal and objectives of groundwater protection, the following integrated measures for groundwater management and protection need to be taken into consideration.

Promote strict management and control of groundwater use

Specify the cap of groundwater use. China is implementing the most stringent water resources management system to control water resources use amount. The goal of controlling national groundwater use to under 1,000 m^3 for 2020, and 950 m^3 for 2030 will be achieved step by step. The control amount of groundwater use for each major basin and each province by 2020 and 2030 was decided in the 'National Groundwater Utilization and Protection Planning'. Based on this control amount for 2020 and 2030, provinces propose their control amounts of groundwater use for each year, and then each province breaks its indexes down to each city, and each city breaks its indexes down to each county. To achieve the goal of groundwater use control amount, 18 provinces need to decrease their groundwater use, and the other 13 provinces may reasonably increase their groundwater use according to the economic development needs.

Implement groundwater table control rules. First, for areas where groundwater is not over-exploited, a minimum allowable groundwater water level has been stipulated as a groundwater water level control indicator. Under normal circumstances, the average water level of a region can reflect the groundwater condition of the region, thus the regional allowable minimum average water level can be seen as the groundwater water level control indicator. However, for some specific areas, such as groundwater centralized water supply sources, the lowest allowable water level indicator should also be set in the center of the water source.

Second, in groundwater over-exploitation areas, the groundwater level is usually expected to keep declining in the long run because the groundwater overuse cannot be eliminated immediately. Therefore, the groundwater table management should include other indexes, such as a decline rate of the water table.

Third, in some areas where groundwater levels are too high and may easily result in soil salinization, an upper limit of groundwater level should be defined, namely, the water table should be reduced to the upper limit by extracting groundwater by other methods.

Fourth, quantifying the groundwater level control index should also take into account the stability of buildings and infrastructure, for example, the groundwater level of areas surrounding the subway should also be limited. Hence, the upper limits of the water table specific for these regions is necessary.

Delimit the prohibited and limited groundwater pumping areas. The Chinese government has proposed to demarcate the areas where the pumping of groundwater is prohibited or limited. Currently, 15 out of 31 provincial governments have designated groundwater prohibited and limited pumping areas. In general, the following areas are classified as prohibited areas for groundwater:

I. Areas where geological environmental problems have occurred such as severe land subsidence, ground fissures, sea (salty) water intrusion, vegetation degradation.
II. Groundwater over-exploitation areas in which water supply problems have been solved through alternative water sources.
III. The protection areas of major infrastructure.

Meanwhile, the principles for demarcation of limited pumping areas are as follows:

I. Groundwater over-exploitation areas other than prohibited pumping areas.
II. Areas in which exploitation quantity is close to allowable exploitation.
III. Areas where the pumping of groundwater may lead to geological environmental problems.
IV. National natural reserves, geological parks, scenic spots and other special protected areas.

For areas designated as prohibited areas for groundwater pumping, the pumping and utilization of groundwater shall be strictly prohibited other than in the following circumstances:

I. Temporary emergency water supply provided for the construction safety of underground works.
II. Temporary emergency water supply to eliminate the hazards for public safety or the public interest.
III. A small amount of water withdrawal for the development of groundwater monitoring, survey and evaluation.

Areas designated as groundwater limited-exploitation areas, in addition to the circumstances described above, except for necessary domestic water use, any other organizations and individuals are prohibited from increasing access of groundwater utilization.

Reduce groundwater over-exploitation

Reduce groundwater exploitation in over-exploited regions. Comprehensive measures should be developed and implemented to gradually reduce excessive exploitation in areas showing significant groundwater depletion.

Reduce over-exploitation for urban domestic and industrial use

The exploited quantity of groundwater in urban areas (including industrial and urban domestic use) in China is 39 billion m^3, accounting for 19% of the total quantity of urban water use. The reduction of groundwater exploitation in highly exploited urban areas can mainly be realized through the measures discussed below.

First, replacing over-extracted groundwater in urban regions with water from some water transfer projects, such as the South-North Water Transfer Project, is the main measure to control the urban groundwater over-exploitation problem. In addition, due to the expansion of urban development, some of the water sources previously used for water supply for rural areas had been diverted to provide water for the urban area (Wang, 2011). These water sources for urban areas can be substituted by water from the water transfer project and again be returned to the rural area water supply, which is one of the means of groundwater over-exploitation control in rural areas.

Second, improvement of water use efficiency. This should be promoted through an adjustment of the industrial structure and the promotion of processes, technologies and appliances that save water, reduce leakage and generally improve the efficiency of water use.

Third, improvement of the use of non-conventional water sources. This should be advanced by encouraging the use of reclaimed waste water and sewage in urban areas and the use of non-conventional water sources such as the desalination of seawater or brackish water or rainwater harvesting.

Reduce groundwater over-exploitation for agriculture

The reduction of groundwater exploitation for agricultural irrigation can be achieved through measures such as efficient water-saving reform, water source replacement, adjustment of agricultural planting structure, reduction of irrigation area, agricultural water-saving and promotion of water-saving crop varieties.

First, development of water-saving irrigation system. The irrigated areas that are relying on groundwater in areas where groundwater is over-exploited should apply modern water-saving technologies.

Second, using more surface water for irrigation. Try to replace groundwater used for agricultural irrigation by adding other water sources such as surface water or reclaimed water. The use of surface water for irrigation can be increased by dredging rivers and lakes, developing water-storage ponds, and improving the inter connection of river system, lake and reservoir.

Third, adjustment of agricultural planting structure. The planting pattern of North China is double cropping a year, with one season of wheat and the other of corn. It is known that the growth of wheat needs a considerable amount of irrigation water. In the region with severe problems of deep groundwater over-exploitation and without surface water available for replacement, the planting area of winter wheat irrigated by groundwater should be reduced, which means that the former double cropping system of winter wheat and summer corn should be changed to a single cropping system of corn, or cotton, or peanut, or sunflower oil, or miscellaneous grains, or other crops.

Enhance groundwater recharge. Increasing the groundwater recharge is one of the effective measures to treat and prevent groundwater over-exploitation. It has been widely used internationally, however, it has not been considered as a main treatment means in China. That is because the standards for the

quality of recharge water are hard to determine and manage. In some regions, such as the water-receiving areas of the South to North Water Diversion Project, the conditions for water recharge are qualified and groundwater recharge should be enhanced. In Hebei and Henan provinces, the diversion water is not completely consumed locally, and the sediment condition is very suitable for groundwater recharge in the piedmont plain, thus diversion projects could be implemented to transfer excessive Yangtze river water to recharge regional groundwater.

Strengthen the prevention and control of groundwater pollution

Comprehensive policies in administration, legislation, economy and technology should be adopted for overall prevention. Two types of policy are involved.

It is necessary to strengthen the research and demonstration on prevention and control technology of groundwater pollution. First, the establishment of a control system for groundwater pollution is indispensable. On the one hand, according to the requirements of traceability management, surface source control should be strengthened, especially to solve the overuse problem of pesticide and fertilizer in China. On the other hand, by means such as the establishment of an automated on-line monitoring system, the relevant authorities should carry out the monitoring of point-source pollution and coercively rectify or close enterprises with over-emission of pollutants. Second, for areas with different geological and hydro-geological conditions, the authorities should choose typical polluted areas to demonstrate the project of groundwater pollution control and water-bearing stratum repair. With the chosen areas mainly polluted by heavy metal, organic pollutants, soil pollutants, etc., providing technical support and demonstration experience for groundwater pollution control is of great help (Wang, 2011).

Meanwhile, it is also important to strengthen pollution prevention of groundwater drinking sources. Combined with the *Overall Plan for Ensuring Safety of Urban Drinking Water Source Areas* (2006–2020) and *National Planning for Prevention and Control of Groundwater Pollution*, on the basis of analyzing the geological conditions and exploration status and protection status quo of the centralized groundwater supply source areas, the authorities could reasonably arrange protection measures, including defining the scope of protection areas, constructing isolation fences, closing the drain outlets, closing and backfilling the abandoned mines, drilling wells and water-intake wells, and building ecological and clean small basins. In addition, strict assessment of the admission system and protection of the water sources should be enhanced.

Reinforce capability building of groundwater management

Optimize groundwater management system. At present, there is no specific law on groundwater management in China. There are several provisions of groundwater management in 'Water Law' and 'Water Pollution Prevention Law', but the provisions are relatively theoretical and not practical. Now, China's Ministry of Water Resources (MWR) is compiling 'Groundwater Management Regulations' at national level, which would specify every regulation of groundwater exploitation and punishment for illegal acts (Wang & Xiong, 2012). Besides, some provinces have published provincial groundwater management regulations, such as Hebei, Shanxi and Yunnan provinces, etc., and due to the differentiations in groundwater conditions, i.e. existing problems as well as focal points in management and protection among provinces, the regulations are not identical.

Establish and improve groundwater monitoring system. First, it is strongly advised to comprehensively improve the groundwater pumping metering rate. For urban public water supply source wells, self-contained water source wells of enterprises and institutions, and rural centralized water supply source wells, etc., an on-line metering system should be realized gradually; for above-scale decentralized agricultural irrigation electro-mechanical wells, metering equipment should be installed for each well (Jing *et al.*, 2013).

Second, dynamic monitoring of groundwater should be strengthened. On the basis of National Groundwater Monitoring projects, local authorities should densely build groundwater monitoring stations according to management needs, improve the publication system of groundwater information, and provide accurate and all-sided groundwater dynamic information so as to satisfy scientific research, and meet the basic requirements of the public on groundwater information.

Strengthen investigation and assessment of groundwater. Dynamic investigation and assessment mechanisms need to be established. Currently, the MWR is responsible for the investigation and assessment of water resources, including groundwater resources, while the Bureau of Land Resources is responsible for those of hydrogeological conditions. The assessment should be operated timely and the data should be shared as the basis for exploitation, management and protection. The assessment of sustainable yield of groundwater resources for maintaining healthy ecosystems should be enhanced. Efforts should also be made to investigate, monitor and research groundwater pollution to determine pollution intensity and distribution, and propose groundwater pollution treatment and ecological restoration to restore groundwater to a reasonable chemical status for groundwater use.

Improve economic adjustment and incentive policies. Low water price is a signal that water resources could be wasted recklessly without costing much. Normally, the water prices do not reflect the scarcity of water resources while the endogenous motivation for the whole of society to save water is insufficient. In this way, the price and tax measures should be promoted to encourage the development of highly efficient water-saving industries with low pollution and low water consumption; economic compensation policies should be adopted to boost the application of water-saving crafts, water-saving appliances and water-saving irrigation technologies. Furthermore, the costs of groundwater should be higher than those of surface water. The costs of groundwater in over-exploited areas should be higher than those in non-over-exploited areas. The relevant authorities should deepen the reform of agricultural water prices, carry out a system of differential pricing for urban residential water consumption and the over-quota progressive surcharges for non-residential water use.

Discussion and conclusion

Groundwater is China's indispensable water supply, especially in north China. Aiming to solve the issues facing groundwater resources in China, including over-exploitation, pollution and weak management capacity, the key strategies and measures for groundwater management and protection can be summarized by four aspects, as discussed below.

First, strictly controlling groundwater exploitation. Groundwater exploitation in China should be gradually decreased from now to 2030 to reduce groundwater over-exploitation and reserve more groundwater resources as strategic reserves and emergency water resources. China is trying to

implement a Total Amount Control System of groundwater exploitation. A control amount of groundwater use should be defined for each region and each basin. The control amount should be adjusted gradually so that the extracted amounts can be progressively reduced in over-exploited areas while increasing them in low-exploited areas to arrive at a balanced supply and demand, compatible with maintaining a stable groundwater level over a yearly cycle.

Second, implementing forbidden and restricted areas management system for groundwater exploitation. The provincial governments should define the forbidden and restricted exploitation areas of groundwater, and then formulate and implement countermeasures (Qiao, 2007). Except for emergency water supply, groundwater in the forbidden exploitation areas would not be allowed to be used; and in the restricted exploitation areas, groundwater would not be allowed to be used for industrial and agricultural production and new service industries.

Third, reducing groundwater over-exploitation. On the one hand, measures including local industrial structure adjustment, agriculture planting structure adjustment, and water-saving techniques should be implemented to reduce water resources' demand in over-exploited regions. On the other hand, utilizing water-diversion projects and other surface water sources projects to provide more surface water sources to replace groundwater exploitation as water supply should be implemented. Furthermore, strengthening the use of non-conventional water sources to complement groundwater exploitation is also important to reduce groundwater use, especially some industry water use.

Fourth, groundwater management capability should be fully enhanced, including promulgating nationwide and provincial specific groundwater regulations and laws; establish groundwater monitoring systems and promote the measurement ratio of groundwater exploitation, optimize groundwater monitoring network; improve economic adjustment and incentive policies and encourage the public to protect groundwater by using market means.

At present, the measures mentioned above have been applied in some plot areas, however, complete implementation still needs some effort.

First, it is necessary to implement the 'total amount control' for groundwater exploitation and strictly constrain the groundwater exploitation of every province and city. However, the measurement rate of groundwater withdrawal is low, and completely accurate implementation of these methods will face difficulty. For example, most of the agricultural irrigation groundwater has not been measured but speculated by per-area irrigation water use based on experience. Except for agricultural wells, some wells dug by enterprises are not included in the management system of the waterworks department, which makes the implementation of 'total amount control' difficult. Currently, many regions have registered and controlled the enterprise-owned wells, and also come up with measures such as installing water meters and calculating water use from electricity use, etc. to achieve the agricultural groundwater measurement. However, more effort is still needed. Many agricultural irrigation wells exist in China, but the cost of metering facilities' installation for all is high. Therefore, a metering method with low cost and accurate measurement is necessary. It may be feasible to calculate the amount of irrigation water from the use of agricultural irrigation electricity. However, for different regions, different irrigation methods, or even different pumps, the relationship between pumped water and electricity consumption is not fixed. Further efforts should be made to find the relationship for each region. In addition, the data for irrigation electricity consumption are managed by the power supply department, and coordination between departments is also crucial.

Second, groundwater plays the role of multi-year regulation of water resources, and keeps the balance of water resource supply and demand in various rainfall years. When allocating water resources, the

function of groundwater that is recharged in wet seasons while draining as an effective water supply in dry seasons should be considered. Thus, when formulating the standards for 'total amount control', the effects of different types of rainfall years should be taken into account.

Third, many problems such as surface subsidence occur as a result of mining deep confined water, meanwhile, considering this resource is hard to refresh, China has brought up the policy that the deep confined water could only be used as contingent and strategic water reserves. Except when there is no alternative source for domestic water use, it is forbidden to extract such water. However, the definition of deep confined water is controversial, while the concept of 'hard to refresh' could hardly be quantified as well.

Finally, in China, the agricultural sector is the largest consumer of groundwater, and groundwater over-exploitation control and management relate to the interests of numerous farmers, therefore, getting support from farmers is key. First, the advocacy of groundwater resources protection should be enhanced to let farmers understand the significance and meaning of groundwater resources protection and be aware of the whole process of the implementation; second, the interests of farmers should be guaranteed. Some approaches of controlling groundwater over-exploitation, such as adjustment of agricultural planting structure, may have certain impacts on the income of farmers, hence there must be a corresponding compensation mechanism so that farmers would not suffer much income loss; third, the technical training of farmers is necessary and should be enhanced to assist farmers to maintain the application of water-saving technologies and facilities, and also to understand the relative water rights, water prices and other management measures.

References

Jing, L., Liu, W., Wang, D., Zhu, Q., Bai, H. & Sun, Y. (2013). The construction and management of groundwater environmental monitoring network in China. *Environmental Monitoring and Forewarning 5*(2), 1–4.

Qiao, S. (2007). Reflections on improving groundwater management and conservation. *China Water Resources 15*, 19–21.

Tang, K., Wu, Y. & Hou, J. (2006). Assessment of groundwater quality in China: II. Groundwater quality and pollution analysis. *Water Resources Protection 22*(3), 1–4.

Wang, Z. (2011). The problem of groundwater overdraft collected in Shanxi province and countermeasures. *China Water Resources 11*, 28–30.

Wang, J. & Xiong, J. (2012). Construction of management system of ground water in China. *Journal of Hohai University (Philosophy and Social Sciences) 14*(2), 62–67, 92.

Wang, Y., Jin, X. & Liu, J. (2000). Research on groundwater development and efficient utilization in China. *Journal of Shijiangzhuang University of Economics 23*(2), 199–210.

Wang, Q., Tan, X. & Chen, J. (2013). Current situation and research progress of groundwater pollution in China. *Environmental Science and Management 37*(B12), 52–56.

Xue, Y. (2012). Discussion on groundwater over-exploitation and ground settlement. *Ground Water 6*, 1–5.

Yang, G., Meng, J., Su, X. & Guo, J. (2012). A brief review of evaluation index and method of groundwater overdraft. *Water Saving Irrigation 8*, 34–38.

Yang, H., Wang, G. & Zhang, Y. (2014). A division scheme of groundwater systems in North China. *Earth Science Frontiers 21*(4), 74–82.

Zhu, Q. & Xu, G. (2009). The current situation and research of groundwater fluorine pollution in China. *Environmental Science and Management 34*(1), 42–44.

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