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A critical review of groundwater utilization and management in China's inland water shortage areas

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Abstract

Groundwater, as an important store of freshwater, plays a more critical role in sustaining the ecosystem and enhancing human adaptation to changing climate than surface water. In particular, it can store large volumes of water to naturally buffer the pressure of water shortage against seasonal changes in rainfall. However, groundwater itself is also vulnerable to climate change, showing a great change in hydrologic cycle. Therefore, effective groundwater management has a strategic importance for China's water security. At present, China is facing a groundwater crisis because of the dual effects of natural and anthropogenic factors. Many new ideas and solutions have been given in previous studies on groundwater utilization and management. This paper vividly captures these studies. The paper summarizes groundwater properties and the situation of groundwater development and utilization. The paper also reports challenges, strategies and policies in groundwater sustainability.

Keywords: Groundwater; Groundwater management; Inland water shortage areas; Water shortage

1. Introduction

The problem of water shortage in inland water shortage areas in China is becoming more and more prominent with China's rapid industrialization and urbanization (Liu *et al.*, 2013). Especially in Northern China areas, due to less rainfall and runoff and uneven seasonal distribution, a large amount of groundwater is exploited and utilized, which has resulted in declining groundwater levels during recent decades (Cai, 2008). Groundwater comes from surface water via infiltration through cracks in rock strata and soil crevices into the ground, and is composed of multi-aquifer systems including shallow, middle and deep groundwater flow systems (Zhu *et al.*, 2004). In a natural state, some groundwater (especially shallow groundwater) will be consumed through land surface evaporation and vegetation transpiration. In some special landform areas, a large amount of surface water seepage into the subsurface may form underground rivers resulting in the loss of the surface water (Yuan *et al.*, 2013). In addition, a great deal of groundwater extraction for use in industrial and agricultural production and people's lives is one of the key factors leading to the large amount of groundwater consumption (Ma *et al.*, 2005).

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Groundwater level is determined by both groundwater sources and groundwater consumption. Only under their equilibrium, can the underground water level maintain a stable state (Hu *et al.*, 2009). The key to the formation and maintenance of this steady state is surface water (Tian *et al.*, 2015). Abundant surface water can effectively increase atmospheric water, and atmospheric water can again further form clouds and become surface water through rain and snow in the circulation of surface water, groundwater and atmospheric water, thus forming a virtuous water cycle system (Ma *et al.*, 2005).

However, the stock of surface water depends on the two aspects of rainfall and water storage. For a particular inland area, rainfall directly affects the runoff of surface water. At the same time, more runoff of surface water will bring more loss of surface water. Therefore, it is necessary to preserve rainfall through water storage facilities such as wetlands and reservoirs to solve the problem of seasonally uneven distribution of rainfall to provide adequate water sources for people's use of water and the recharge of groundwater (Zhu *et al.*, 2004; Liu *et al.*, 2013). Clearly, adequate rainfall and effective storage of rainfall are the key factors affecting the source and the recharge of groundwater. However, abnormal climate changes make normal recharge and maintenance of groundwater more difficult in inland water shortage areas. On the other hand, demand for groundwater is growing with the development of industry and cities in inland areas, leading to a declining groundwater level (Webber *et al.*, 2008a, 2008b). Moreover, the loss of a large number of wetlands and forest cover caused by human activities and improper intervention has caused the normal circulation of groundwater and surface water to be destroyed (Jiang, 2009).

On the other hand, groundwater pollution has become increasingly prominent. Firstly, a large amount of industrial and domestic wastewater without strict treatment has been directly discharged into rivers through infiltration or irrigation resulting in pollution of corresponding regional groundwater (Ma *et al.*, 2009a, 2009b; Gu *et al.*, 2013; Li *et al.*, 2014). Especially in suburban and industrial agglomeration areas, this problem is becoming increasingly serious such that groundwater in some areas has been seriously polluted and often cannot be used (Han *et al.*, 2014a; Yao *et al.*, 2014). Secondly, the pollution of groundwater caused by animal feces produced from livestock farms without strict treatment, and fertilizer and pesticide used for crops, has caused more and more serious problems in some rural areas (Liu *et al.*, 2005).

The inappropriate planning and management of water resource utilization is one of the most important factors, too. To begin with, the development planning of the regional socio-economy is not built on the corresponding bearing capacity of water and other natural resources, resulting in over-exploitation and utilization of groundwater (Zhu *et al.*, 2004). In addition, the task of environmental protection and integrated planning and management of water resources has not been adequately done, causing regional groundwater imbalances and unsustainability (Qadir *et al.*, 2007; Read *et al.*, 2014).

To date, substantial publications on groundwater management in China's inland water shortage areas have mainly focused on the properties of groundwater, the present situation of development and utilization of groundwater resources, and the environmental problems caused by over-use of groundwater. This paper will put forward relevant strategies and policies based on the further comprehensive discussion of these problems, and it is expected that this review will be useful for researchers as well as practitioners, and planners and managers of water resources.

The paper's structure arrangement is as follows. Section 2 discusses the situation and challenges of groundwater development and utilization in China's inland water shortage areas. The third section explains the causes for and factors contributing to the groundwater level declining. In section 4, the paper addresses strategies for rational groundwater utilization and a new management paradigm. Section

5 explores the associated policies of groundwater utilization and their economic assessment. The final section presents conclusions.

2. The situation and challenges of groundwater development and utilization in China's inland water shortage areas

2.1. The overdevelopment of groundwater and the continuously declining regional groundwater levels

Floods, droughts and water shortages, and water pollution have made tremendous impacts on China's economic and social development. In particular, droughts and water shortages have become one of the most prominent problems restricting social and economic development. As a component of total water resources, groundwater has played a dominant role in China's water supply. In recent years, groundwater has been exploited on a large scale because of surface water shortages. However, the groundwater recharge rate from surface water has greatly been reduced, which has resulted in declining groundwater levels (Zhu *et al.*, 2004; Jiang, 2009).

The underground water level in Jilin, Shandong, Henan, Shaanxi and Ningxia was in a relatively stable state (change from −0.1 m to 0.1 m), while the underground water level in the remaining half of the regions was significantly declining in North China's plain areas (Ministry of Water Resources of the People's Republic of China (MWRPRC), 2011). In addition, the pressure of the declining of groundwater level in the relatively stable regions of groundwater still exists with the development of industrialization and urbanization (Zhou *et al.*, 2012) (see Table 1). It is expected that the development and utilization of groundwater will increase with rapid industrialization and urbanization and growing demand for water resources in the future.

In fact, the groundwater level in many parts of China (especially in the North China Plain) has declined continuously since 1960. The excessive development and utilization of groundwater is one of the most important factors. Under the dual effects of natural and anthropogenic factors, the groundwater level at a specific time and region will continue to decline with the reduction of rainfall, especially in Northwest China areas (Zhang *et al.*, 2006). Due to the excessive development and utilization of groundwater and the reduction of groundwater recharge caused by the concentrated exploitation of fresh groundwater, soil cracking and depression cones are formed which accelerate groundwater evaporation and leakage, in turn exacerbating the declining groundwater levels (Yang *et al.*, 2002).

2.2. Eco-environmental problems caused by the overdevelopment of groundwater

2.2.1. Changes in groundwater quality. The changes in groundwater quality are caused by the dual impacts of human factors and the self-inflicted factors of the hydraulic system. Considering human factors, industrial production will undoubtedly produce a large amount of industrial wastewater containing a large number of harmful inorganic substances. Agricultural production and people's daily life will produce large amounts of wastewater containing large amounts of harmful inorganic and organic emissions, too. If these wastewaters are not made harmless by treatment but are discharged and permeated into the soil, they will pollute the groundwater (Geng *et al.*, 2014).

On the other hand, a significant decline in groundwater level will inevitably change the stress state of the groundwater system and accelerate the vertical and horizontal migration of groundwater, possibly

Table 1. The change of groundwater level in the North China's plain areas from 2008 to 2011.

	Average change in groundwater level (m)			
Regions	Jan. 1, 2008 to Jan. 1, 2009	Jan. 1, 2009 to Jan. 1, 2010	Jan. 1, 2010 to Jan. 1, 2011	Accumulation for 3 consecutive years
Beijing	−0.15	−1.13	−0.75	−2.03
Tianjin	+0.41	−0.10	−0.06	+0.25
Hebei	+0.19	−0.10	−0.47	−0.38
Shanxi	−0.18	−0.24	−0.23	−0.65
Inner Mongolia	−0.06	−0.43	−0.10	−0.59
Liaoning	+0.28	−0.32	+1.43	+1.39
Jilin	+0.22	−0.48	+0.29	+0.03
Heilongjiang	−0.10	+0.45	−0.05	+0.30
Jiangsu	−0.25	+0.30	−0.32	−0.27
Anhui	−0.20	+0.33	−0.64	−0.51
Shandong	+0.04	+0.06	−0.02	+0.08
Henan	−0.22	+0.11	+0.04	+0.07
Shanxi(Xian)	−0.29	+0.11	+0.13	−0.05
Gansu	−0.21	−0.05	−0.04	−0.30
Ningxia	+0.08	0.00	−0.04	+0.04
Qinghai	−0.36	+0.99	+0.58	+1.11
Xinjiang	−1.02	−0.15	−0.06	−1.23

Source: The Ministry of Water Resources of the People's Republic of China (MWRPRC) (2011).

resulting in the migration of poorer quality groundwater into good quality aquifers (Han, 2003; Han *et al.*, 2014b). In addition, the declining of the groundwater level and the groundwater stock shortage will reduce the self-purification capacity of the groundwater system. Without artificial intervention, the increasing deterioration of groundwater quality is inevitable. Some regions have even experienced the phenomenon of saltwater intrusion.

The emissions of wastewater and its harmful substances in China are very large, but most are not effectively treated (see Table 2). In recent years, although the state has taken strict environment protection measures and wastewater has been adequately treated, yet pollution caused by wastewater is still serious due to the growth of total wastewater emissions. Much of the wastewater is directly or indirectly transformed into groundwater, resulting in the deterioration of groundwater quality, so that groundwater in some areas cannot be used.

2.2.2. Land subsidence. Land subsidence caused by the over-exploitation of groundwater has become increasingly serious in many arid and semi-arid regions. Studies have demonstrated that there is a close positive correlation between land subsidence and groundwater level (Cao *et al.*, 2013). The North China Plain, Yangtze River Delta region and Fen-Wei Basin are the most serious areas of land subsidence since 1959, while these regions are also the most deficient areas of groundwater in China (see Table 3). Due to extensive groundwater pumping, the compaction of sediments after subtracting pore water in the aquifer is greatly reduced, which is the main reason for the subsidence (Han, 2003).

Table 2. The emissions of main pollutants in wastewater.

The emissions of main pollutants	2011	2012	2013
Total wastewater (TTT)	6,591,922.44	6,847,612.14	6,954,432.7
Chemical oxygen demand (TTT)	2,499.86	2,423.73	2,352.72
Ammonia nitrogen (TTT)	260.44	253.59	245.66
Total nitrogen (TTT)	447.08	451.37	448.1
Total phosphorus (TTT)	55.37	48.88	48.73
Oil emissions (tons)	21,012.09	17,493.88	18,385.35
Volatile phenol (tons)	2,430.57	1,501.31	1,277.33
Lead (kg)	155,242.00	99,358.81	76,111.97
Mercury (kg)	2,829.15	1,223.44	916.52
Cadmium (kg)	35,898.98	27,249.89	18,435.72
Total chromium (kg)	293,166.34	190,079.08	163,117.68
Arsenic (kg)	146,615.97	128,493.75	112,230.03
Six valence chromium (kg)	106,395.37	70,533.80	58,291.45

TTT indicates ten thousand tons.
Source: http://www.stats.gov.cn.

Table 3. The most serious areas of land subsidence since 1959.

Areas	Cumulative subsidence over 200 mm (km^2)	Ratio in total land areas (%)
North China Plain	62,000	46
Yangtze River Delta Region	10,000	30
Fen and Wei River Basin	7,000	10

Source: http://www.mlr.gov.cn.

At present, the cities which have experienced land subsidence disaster have exceeded 50, located in 20 provinces and municipalities such as Tianjin, Hebei, Shanxi, Inner Mongolia and others. Especially, the regions with a cumulative amount of land subsidence greater than 200 mm have reached 79,000 km^2 with an increasing trend. Among them, the Yangtze River Delta region, the North China region and the Fen and Wei River basin are three major areas (see Table 3). According to the national statistics, more than 100 cones of depression have formed, covering an area of 150,000 km^2 (Ministry of Land Resources of the People's Republic of China (MLRPRC), 2012).

2.2.3. Soil degradation and vegetation ecosystem destruction. China is a country with a wide distribution of desert and desertification land and about 27% of the country's land area has undergone desertification, while potential desertification land is about 160,000 km^2. Land desertification in China is showing a trend of accelerated expansion with an increase of 2,460 km^2 or so each year. In addition, another 60 million acres of farmland are at risk of desertification (MLRPRC, 2011).

The significantly declining groundwater level caused by the excessive development and utilization of groundwater is one of the most important factors. Research indicates that there is a significantly positive correlation between desertification, salinization or stone desertification and the declining groundwater level. As shown in Figure 1, Xinjiang, Inner Mongolia, Xizang, Gansu and Qinghai are the most serious

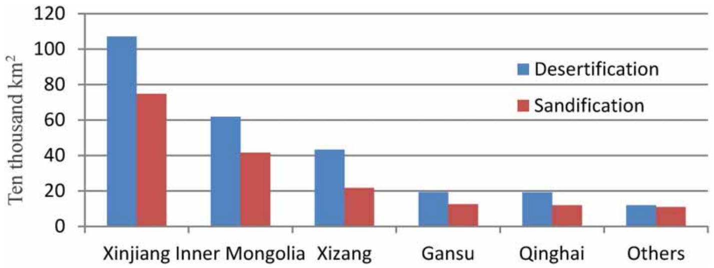

Fig. 1. The most serious areas of desertification and sandification in China by the end of 2009.

areas of desertification and sandification in China, while these regions are also the most deficient in surface water and groundwater. In recent years, desertification in China has accelerated. However, in addition to abnormal climate changes, another major reason for this is the growing demand for groundwater caused by the rapid development of society and economy (Cui & Shao, 2005).

Adequate soil moisture is the basic condition required for the growth of vegetation. If groundwater is excessively exploited and utilized, it will lead to a significant reduction of groundwater level, which will further lead to a change in vegetation species and types or even serious consequences of vegetation degradation and oasis shrinking (MLRPRC, 2011; Peng *et al.*, 2015). A notable area where this has occurred is Northwest China. Northwest China was originally an oasis, but the dual influences of natural rainfall reduction and artificial over-exploitation of water resources has resulted in a significant reduction of groundwater levels.

The long-term decline of groundwater levels has resulted in vegetation degradation, the death of desert plants and the degradation of windbreak and sand fixation forests and other serious ecological problems in the region. Even a *populus euphratica* forest with a strong drought resistance capacity has suffered a large area of dead vegetation in recent years (Zhang & Chen, 2011). In fact, in China's many arid and semi-arid regions, vegetation degradation and species variation have emerged to varying degrees.

3. The causes and factors affecting groundwater level decline in China's inland water shortage areas

3.1. Effect of regional water scarcity on groundwater level

Abnormal climate change, socio-economic development and unreasonable water use have resulted in serious water shortages in China's many inland areas in recent years. Serious water shortage causes not only groundwater source reduction and difficult recharge for groundwater, but also leads to water reduction in reservoirs, rivers, lakes and wetlands, which will in turn lead to further reducing the probability of atmospheric water formation and rainfall in specific areas to cause a vicious circle in water shortage. Water shortages in the north and central China regions have become increasingly serious, leading to China attempting to alleviate this problem through the South to North Water Transfer Projects (Liu *et al.*, 2014).

Serious water shortage has still resulted in a sharp growth in the exploitation and utilization of groundwater to exceed the carrying capacity of groundwater in particular areas, causing the declining groundwater level. In the North China areas, a sharp decline in the groundwater level caused by the excessive exploitation and utilization of groundwater has resulted in the consequences of groundwater depletion. Even some inland areas, which were earlier rich with water, have also seen water shortage lead to great exploitation and use of groundwater because of industrialization and urbanization development, water pollution and inappropriate water planning and management, causing the declining groundwater level (Zhang *et al.*, 2008). In fact, the influence of regional water shortage on groundwater is difficult to estimate.

3.2. Industrialization, urbanization and groundwater development

Industrial water consumption accounts for about 21% of the total national demand for water, which is the second-largest water consumption sector behind agriculture. The development of industries, especially high water consumption industries such as thermal power, papermaking, steel, textile, chemical and mining industries, consumes a large amount of water. Therefore, large-scale industrialization throughout China will inevitably result in an exponentially-growing demand for water. In fact, the annual average growth rate of industrial development demand for water in recent years is more than 5% (Webber *et al.*, 2008a, 2008b). For inland water shortage areas, groundwater is an important source of water supply. For example, 35–50% or so of water supply in North China comes from groundwater (Jiang, 2009). In some inland areas with serious water shortage, demand for groundwater has a significantly high correlation with industrial development in the area.

There is a positive relationship between urbanization level and total water utilization during rapid urbanization especially in China's arid and semi-arid areas, and the water resources constraint force will become greater and greater with urbanization development (Bao & Fang, 2007). In fact, the essence of urbanization is demographic urbanization, but large populations concentrated in cities will consequentially increase the demand for water. In addition, with the improving life quality of urban residents, people's demand for water will increase greatly, too (Wang *et al.*, 2014). However, a great deal of groundwater must be exploited and utilized with rapid urbanization because of the surface water shortage. Therefore, how to augment groundwater resources has become one of the important parts of water management strategy in water shortage cities.

3.3. Agriculture and groundwater development

Agricultural water consumption accounts for about 64% of the total national demand for water, being the largest water consumption sector. Agricultural irrigation needs huge quantities of water. In inland water shortage areas such as the North China Plain, because surface water is limited and restricted for urban water supply, agricultural production heavily relies on groundwater, accounting for 60–70% of total groundwater utilization (Hu *et al.*, 2010).

However, because agricultural irrigation water has the characteristics of strong evaporation and low utilization rate of water resources due to flood irrigation, the effect of agricultural development (especially intensive agricultural development) on groundwater is more significant (Xu *et al.*, 2005; Zhang *et al.*, 2014). In addition, the conversion of surface water, soil water and groundwater is more complex in arid or semi-arid areas, which deepens the impact of agricultural development on groundwater level, too (Tian *et al.*, 2015). Agricultural production has thereby become the main driver of groundwater depletion in China's arid and semi-arid areas.

3.4. *Climatic change and rainfall reduction*

The effects of climate change on groundwater include the two aspects of groundwater demand and groundwater recharge. Climate change, especially more frequent and intense climate extremes (e.g., droughts, floods, etc.), will lead to unbalanced distributions of rainfall both in temporal and in spatial scale. In the temporal distribution of rainfall, people's demand for water is relatively stable, but extreme climate change may cause rainfall concentration in a season, resulting in excess supply of rainwater in the rainy season and the waste of water, but a shortage of rainwater supply in the dry season. Considering the spatial distribution of rainfall, extreme climate change may cause some areas to have more rain and floods but other areas to have insufficient rainfall and drought. For a specific region, demand for groundwater in the dry season increases, and at the same time groundwater recharge reduces, too.

In fact, local rainfall makes a significant contribution to groundwater recharge. Severe desertification areas in North China were originally an oasis, but later large reductions in rainfall caused by extreme climate change and the increasing demand for groundwater finally resulted in the declining of the groundwater table leading to serious desertification (Ma *et al.*, 2003, 2013; Wang *et al.*, 2013). Many arid or semi-arid areas have exhibited periodic declining of the groundwater table and desertification trends in different degrees due to extreme climate change, too. Therefore, how to deal with extreme climate change has become one of the important strategic measures of future groundwater management.

4. Strategies for rational groundwater utilization and new management paradigm

4.1. *Risk analysis and dynamic assessment*

As an important source of fresh water, the development and utilization of groundwater is essential. Especially, it is more important for arid and semi-arid areas to develop and utilize groundwater. The key is that the development and utilization of groundwater must be based on the carrying capacity of specific regional groundwater to achieve balance and sustainability of the groundwater. It is necessary to analyze and evaluate the development and utilization situation and risks to groundwater, including the quantity and quality of groundwater and the ecological risk and pressure caused by over-development and utilization of groundwater (Wei *et al.*, 2014).

Groundwater resources in specific regions will change significantly because of abnormal climate change and strong human impacts, leading to the requirement for dynamically comprehensive analysis and assessment of groundwater resources to provide a scientific decision-making basis for social and economic development (Jia *et al.*, 2006). Especially for arid and semi-arid areas, water safety is not only concerned with social, economic, ecological and environmental problems, but also may affect national security. Therefore, strengthening monitoring and carrying out dynamically comprehensive analysis and assessment of groundwater resources in these areas have strategic and practical significance (Xiao *et al.*, 2008).

4.2. *Integrated water planning and management under climatic uncertainty*

In extreme climate change and with the growing shortage of water resources, the most important measures to solve the shortage of water resources are to create a strategic decision-making system and improve strategic planning for water resources (Read *et al.*, 2014). For groundwater resources, the first issue is the river basin planning of groundwater resources. Because every river plays a decisive role in the maintenance and supplementation of groundwater resources to the corresponding region, it is necessary to rationally allocate water resources in the river between the upstream and downstream regions to ensure enough water resources for downstream areas. The key to the river basin planning of water resources is the planning and layout of industry and city development in corresponding basin areas, while industry and city development in the basin areas must be based on the carrying capacity of available water resources (GWP, 2009; Shen, 2009).

The second issue is the planning and management of inter-basin groundwater resources. Because of the unbalanced geographical distribution of water resources in China, it is necessary to plan and utilize water resources on a nationwide scale. At present, China has implemented the South to North Water Transfer Projects, which will help to ease the pressure of groundwater in the North China areas (Feng *et al.*, 2007; Ghassemi & White, 2007; Cheng & Hu, 2012). As vast territory areas, the Northwest China areas should carry out the inter-basin planning of sub-regional water resources to realize the integrated planning and management of water resources in the Northwest China areas, too (Ji *et al.*, 2006; Ge *et al.*, 2013).

The final issue is the planning and management of groundwater resource allocation between the city and the countryside and between the industrial and agricultural sectors. In many areas with a serious shortage of water resources, the priority has been to ensure the city's and industry's demand for water resources is met, increasing water demand pressure in the countryside and for agriculture. In the future, it will be necessary to rationally allocate water resources between the city and the countryside and between industry and agriculture to completely solve the problem of groundwater resources depletion in these areas (Cai, 2008; Shen & Liu, 2008; Huang *et al.*, 2012; Wang *et al.*, 2015).

4.3. The improvement of water utilization efficiency

China's economy has been maintained through extensive growth for a long time. Therefore, the waste of water in industry, agriculture and people's life is serious, while water-saving potentials are huge. In terms of industrial water utilization, water consumption in China's industrial added value per ten thousand Yuan RMB is about 78 m^3 and water consumption in China's GDP per ten thousand Yuan RMB is 129 m^3 or so, according to the statistics of the Ministry of Water Resources of the People's Republic of China (2011), while the world's average values are about 50 m^3 and below 80 m^3, respectively. The reuse rate of industrial water in China is about 60–65%, while the recycling rate of industrial water in developed countries is around 80–85%. Therefore, water-saving potentials in China's industrial fields are huge. At the same time, as water use in industrial sectors is more concentrated, so water-saving measures are easier to implement and water-saving costs are relatively small (Li & Ma, 2015). Therefore, it will be one of the most popular water-saving areas in the future.

Agricultural water consumption in China's total water consumption accounts for 64% or so, but the effective utilization rate of water is only about 45%. If the water utilization rate in agricultural irrigation increases by 10–15%, then it can reduce the irrigation water required by $6–8 \times 10^{11}$ cubic metres every year. In fact, the world's average agricultural water utilization rate is 70–80%, but China is far below this standard. Obviously, water-saving potentials in the field of agriculture are huge. In particular, there are many avenues for water-saving in agriculture. For example, the promotion of water-saving irrigation technology, the development of water-saving agriculture, water-saving in horticulture and aquaculture, water-saving in rural life, and so forth. If water-saving potentials in agriculture are fully developed, then it will greatly improve the shortage of water and reduce the utilization of regional groundwater (Cao *et al.*, 2015; Yan *et al.*, 2015).

Water-saving potentials in the cities are huge, too. In addition to that of urban industrial water utilization, the efficiency of residents' living water and public water utilization in cities is low, too. As the water price for urban residents has been too low for a long time, it has led to a serious waste of water. At the same time, it is difficult to completely treat wastewater from residents' living and hence this pollutes the environment. Therefore, improvement of the efficiency of living water consumption is a basic requirement to solve the shortage of water and improve the water environment in cities. The waste in public water use, including public toilet water, urban wetland water and urban greening water consumption, is the most serious, and efficiency improvement in public water use will save a large amount of water.

4.4. Groundwater recharge

The reduction of groundwater recharge is caused by both increasing use and rainfall reduction caused by abnormal climate change (Ma *et al.*, 2005; Yuan *et al.*, 2013). Without doubt, more groundwater will be used in the future with population growth and socio-economic development (Ma *et al.*, 2013). Therefore, artificial groundwater recharge is necessary. The key to this is the construction of massive water conservancy projects. In past decades, China has constructed a large number of dams and reservoirs, water transfer projects and irrigation infrastructures, and they have played an indelible role in alleviating water shortage and enhancing groundwater recharge (Liu *et al.*, 2013).

In addition to the construction of more water facilities, China has to extensively reconstruct an advanced wetland system in the future. Wetland systems can not only effectively keep water and enhance groundwater recharge, but can also improve the regional climate and environment to increase the probability of rainfall in the area, which has a comprehensive role in the growth and protection of water and other ecological resources (Huang *et al.*, 2010; Xie *et al.*, 2013). In fact, the function of wetlands is various. Restoration and construction of a wetland system with the combination of aquatic farming and fisheries development can not only solve the problem of the over-exploitation and use of regional groundwater, but can also greatly improve agricultural structure and promote the production of agricultural products of high quality. Especially, due to its low costs and quick effects, its environmental and economic benefits are significant.

Another effective method of achieving groundwater recharge is to implement inter-basin water transfers. China has launched the South to North Water Transfer Projects, effectively alleviating the problem of the excessive exploitation and use of groundwater in the North China Plain. For severe water shortage areas in Northwest China, it may launch the inter-basin water transfers in the sub-regions. In fact, solid water resources in the form of glaciers and snow in Northwest China are rich, and they are the main source of inland river water. If this region constructs water preservation and transfer facilities at the source to evenly regulate water resources, then it may make full use of these water resources to effectively alleviate the problem of water shortage in Northwest China areas.

4.5. Non-conventional water resources utilization in water-scarce areas

The development and utilization of non-conventional water resources is necessary for regions with scarce conventional water resources. In fact, non-conventional water resources, such as desalinated seawater and highly brackish groundwater, rainfall-runoff water captured by water harvesting and marginal-quality water resources (e.g., wastewater, agricultural drainage water, saline and/or sodic groundwater, etc.), can be used in many fields and thereby are an important supplement to conventional water (Qadir *et al.*, 2007). In particular, the wastewater from domestic, municipal and industrial activities, if properly treated, has great potentials for food, feed, and fish production (Hanjra *et al.*, 2012; Sato, 2013). At present, the development and utilization of non-conventional water has not been given enough attention in some areas due to technical and cost factors. With the growing water shortage, it is necessary to change this situation to cut the demand for groundwater and alleviate the problem of water resource deficiency.

4.6. Underground reservoir construction and protection

Some geologic storage structures in arid and semi-arid areas are suitable for underground reservoir (aquifer storage and recovery) construction. The construction of an underground reservoir can not only save a lot of water resources, but can also improve the ecological environment. For example, it can help to uplift the groundwater level through artificial recharge for groundwater to reduce the formation of depression cones and the ground subsidence caused by the excessive exploitation of groundwater, to restore wetland areas, to ease land desertification and so forth (Ma *et al.*, 2009a, 2009b). Many countries, such as the United States, Sweden, Holland and Germany, actively launch underground reservoir construction for aquifer storage and recovery. China's areas with good underground reservoir construction conditions should actively construct underground reservoirs to give full play to China's role in regulating water resources and the artificial recharge of groundwater.

In fact, an underground reservoir has significant advantages compared to a surface reservoir. For example, it may effectively reduce reservoir evaporation loss in arid or semi-arid areas which causes a huge waste of water resources, and it may reduce the formation of depression cones and ease ground subsidence caused by the over-exploitation of groundwater through artificial water recharge to uplift underground water level, and it is conducive to the recovery of wetland areas and may alleviate land desertification and sandification, and so forth. In particular, as its construction costs are much lower than that of the same size of surface reservoir, it has very significant economic feasibility. Therefore, for some arid and semi-arid areas, especially the Northwest China areas, the promotion of the construction of underground reservoirs has practical significance in enabling China to play its role in the regulation of water resources (Xu *et al.*, 2004; Du *et al.*, 2008; Deng, 2012).

5. The associated policies of groundwater resources utilization and their economic assessment

5.1. Water pricing reform

Water price plays a crucial role in water resources management. However, current water pricing in China is irrational in both price level and price structure. The pricing of different types of water such as municipal water, agricultural water, recycled water and desalination water does not reflect the market characteristics of water respectively, thereby constraining the effects of water price on the supply and demand of water resources. Therefore, China has to improve the water pricing policy, such that water prices fully reflect the scarcity of water resources and the supply and demand characteristics of different types of water, to give full play to the role of price mechanism in the regulation and allocation of water resources (Liu *et al.*, 2009).

The existing research gives different conclusions on the impacts of water price on agricultural irrigation water demand. Balali *et al.* (2011) concludes that water pricing may considerably reduce agricultural demand for groundwater with a non-linear dynamic programming method. However, other research argues that water pricing, especially irrigation water pricing alone, is not a valid means of significantly reducing agricultural irrigation water consumption (Yang *et al.*, 2003; Han & Zhao, 2007; Webber *et al.*, 2008a, 2008b). In fact, much of agricultural irrigation water comes from farmers' self-built dams or free groundwater extraction in many places, but this water is not affected by water price. This is one of the important causes of the water pricing policy failure.

Different from agricultural water consumption, households' and industrial water consumption is significantly affected by water price, as their water supply comes from a centralized water supply system. For households' water consumption, the key is how to properly set the reasonable price of water. For serious water shortage areas, it is necessary to give comprehensive consideration to the two aspects of demand-side and supply-side to set an effective water price, which can encourage the residents to save water. Of course, the poorest households need to be properly subsidized (Chen & Yang, 2009). Similar to residents' water consumption, the role of water price in industry (especially high water consumption industries) is also very significant, as it can significantly raise the production costs of enterprises. Moreover, the costs of policy implementation are relatively lower, due to the relative concentration of industrial water use.

5.2. Water rights and their trading

Trans-jurisdictional and inter-sectoral trading in water rights is becoming an important way to improve distributive efficiency in water resources with the increasing shortage of water resources. Compared to traditional administrative allocation, market-based water allocation may effectively ease water sharing conflicts and improve water use efficiency with the greatest incentives to increase sector-wide and basin-wide benefits (Zhang, 2007; Zhao *et al.*, 2013).

China initiated a pilot project for a tradable water rights system in the Zhangye City of Northwest China in 2002, but it is not well enforced. In fact, the prerequisite for efficient water rights market operation is a reasonable definition and distribution of total water rights or quotas based on a good hierarchical management system (Takahashi *et al.*, 2013). However, because of the great difference in water resources distribution in different regions, it is very difficult to establish a national water rights trading market, while the establishment of regional water rights trading markets can only play a limited role. Therefore, how to establish an effective water rights management system to remove the barriers to water rights trading is the key problem that must be resolved in the future.

5.3. Water resources tax

Generally, water resources tax can not only save water and protect the environment, but can also potentially yield other economic benefits. However, the potential impacts of water resources tax in developing countries are still limited. Some research has indicated that water tax policy only raised a country's or local government's fiscal needs, but did not benefit the economy (Kilimani *et al.*, 2015). Since China's rural Tax-for-Fee reform (Fei Gai Shui), excessive fiscal burden on peasants has been greatly relieved, but water resources consumption and agriculture production has not been improved significantly. Water resources tax only induces a dependence on local water resources such as water ponds and groundwater, but it cuts reliance on regional water sources (Mushtaq *et al.*, 2008).

Unlike mineral and oil resources, water resources have the characteristics of inter-basin mobility and partly public goods on water sharing between different regions. At the same time, demand for water has strict rigidity. Therefore, the scope and rate of taxation in different river basins and their distribution and utilization between different administrative regions are complicated. This determines that the short-term effects of taxation are not significant. However, in the long term, it can improve water utilization rate and save water resources. At present, China's water resources tax is still in the pilot phase. Therefore, China has still to reform and improve the tax structure and taxation system to give full play to its role in saving water resources and yielding other economic benefits in the future.

5.4. Economic assessment of different policies

In theory, in a good economic system, the effects of all policies are equivalent. However in practice, the effects of different policies often have a considerable number of differences due to the inherent defects of the economic system and the restrictions of policy implementation conditions. As shown in Table 4, there is a great difference between water price, water rights trading and water resources tax in terms of their implementation costs, acceptability, policy risks and others. Although water rights trading has even more flexibility, it needs a good trading platform and mechanism. Water price seems to be easily practiced, but its impacts on agriculture in the short term are limited. The short-term effects of water resources tax seem not to be significant, but its long-term effects are considerable.

In fact, the effects of using only a single policy are necessarily limited. To achieve the desired effects, it is necessary to adopt various policies to achieve the complementary relationships between them (Veettil *et al.*, 2011). Another difficulty with the implementation of the policies is that policy designers have

Table 4. The comparison and economic assessment of different policies.

Item	Water price	Water rights trading	Water resources tax
Cost effectiveness	Lower	Least	Higher
Acceptability	Dependence on welfare effects and price structure	Dependence on associated conditions including hard and soft facilities	Dependence on use and distribution of tax revenues
Implementation condition	Fair price level and rational price structure	Good trading scheme design and initial water rights allocation	Effective measure of source water and river basin water
Complexity of scheme design	Relatively simple	Relatively complex	Relatively simple
Efficiency and effectiveness	More to improve households' and industrial water efficiency	Dependence on trading scheme design and initial water rights allocation	Dependence on taxation scope and tax structure
Policy enforcement mechanism	Centralized command-and-control methods	Decentralized market simulation schemes	Centralized command-and-control methods
Policy risks	Likely negative effects on agriculture	Dependence on reasonable definition and distribution of total water rights or quotas	Dependence on the use and distribution of tax revenues

to make a trade-off between agricultural, industrial and residents' water needs and to choose an effective policy composition according to actual conditions for economic and social development, which will test the ability of the government's policy.

In addition, other policies, for example, new irrigation technology extension policy, investment preferential policies for water infrastructure construction and so forth, are good water demand management tools, too. At the same time, China has to improve the institutional, legal and regulatory arrangements of water management and to reform and improve water resource management to improve the use efficiency and equitable allocation of water resources (Jiang, 2009; Liu & Speed, 2009).

6. Conclusions

Rapid economic growth and urbanization in China has presented great challenges to groundwater development and utilization due to a scarcity of water resources. As the important store of freshwater, groundwater plays a more critical role in sustaining the ecosystem and enhancing human adaptation to a variable and changing climate than surface water. However, groundwater itself is also vulnerable to climate change and has shown a great change in hydrologic cycle. Therefore, groundwater management has strategic importance for China's water security.

In inland water shortage areas in China, serious groundwater pollution, and declining of the groundwater level or even groundwater depletion has appeared due to excessive exploitation and use of groundwater at this stage, seriously affecting regional water security. Therefore, strengthening the protection and management of groundwater resources and maintaining the balance and sustainability of groundwater resources have been imperative.

Recent work done indicates that the core of groundwater protection and management is to implement integrated groundwater planning and management based on scientific risk analysis and dynamic assessment. Due to climatic uncertainty, it is necessary to take comprehensive measures for artificial groundwater recharge. At the same time, price and other policies must be used to improve water use efficiency to save water.

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