Climate change and groundwater resources in China

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Abstract: Water resources play an important role in supporting the economic and social development of China. The impact of climate change on water resources has become a bottleneck in this process, especially for major projects, with surface water and groundwater systems experiencing considerable impacts. The annual natural recharge of fresh groundwater is 8 840×10^8 m^3, which accounts for approximately 31% of the water resources. Groundwater is the most significant water source for many cities and energy bases, and it is also the main source acting as a buffer against extreme climate events caused by climate change. However, most of the groundwater in China buried deeply and unevenly, which increases the difficulty of investigating and exploiting this resource.This paper illustrates the general conditions of China water resources and hydrogeological hazards, such as karst sinkholes, surface subsidence, and soil salinization, caused by climate change, El Nino, La Nina, other climate events and human activities and presents the regulatory measures enacted to mitigate these issues in China.The China Geological Survey (CGS) has organized professional teams to investigate and evaluate groundwater resources and the environment since 1999. Based on these investigations, the total quantity, expected exploitable quantity and current exploited quantity of groundwater in whole China have been evaluated. In addition, an evaluation of the groundwater pollution caused by climate change throughout China and key areas has been conducted. At present, the CGS is conducting national groundwater monitoring projects and establishing regional engineering and technical measures for water resource exploitation and utilization.

Keywords: Groundwater; Water resource; Climate change; Hydrogeological hazard; Technical measure; China

1 Introduction

1.1 Status of groundwater in China

1.1.1 Climate and water resources

The general drainage system pattern in China is influenced by the following 3 main factors: Geographic position, monsoon area, and topography. China is mainly located in a temperate zone, and tropical monsoons from the Indian Ocean and Pacific Ocean are responsible for considerable precipitation in China. The precipitation in China differs according to the elevation and topography. The overall length of all rivers in China is approximately 420 000 km, and the drainage area for 50 000 rivers is larger than 100 km^2, and approximately 1 500 of these drainage basins are over 1 000 km^2.

The annual mean average precipitation is 649 mm, which is varies annually. As shown in Fig. 1, from 1951 to 2002, the total precipitation decreased at an average of 0.569 mm/yr because of the decreased rainfall in spring and autumn (WANG Ying *et al*. 2006). In the north, the precipitation level in a year with abundant rain could be 3 to 6 times higher than that of year with low rainfall. This variation in rainfall leads to changes in the runoff volume, which could differ by 10-fold in the same river. The distribution of rainfall at different spatial scales is also uneven. Greater rainfall occurs in the eastern and southern areas than in the western and

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northern areas. Precipitation in summer accounts for 47% of the total for the whole year, although in the north, this value can reach 62%. The annual runoff depth is 280 mm (GUO Jing-hui, 1958; YOU Song-cai *et al*. 2002), and values of 666 mm have been observed in southeast areas, although the value decreases to 35 mm for certain rivers in northwest areas. Another outstanding feature of precipitation in China is the combination of rain and heat in the same period.

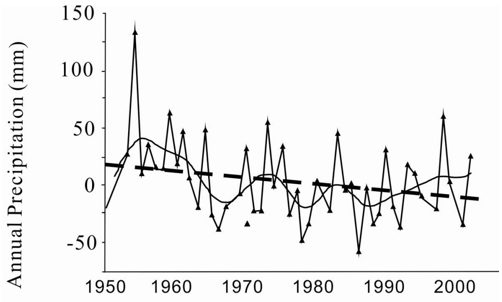

Fig. 1 Annual precipitation of China from 1951 to 2002

In addition to precipitation, the other main factor that limits water resources is evaporation, which is affected by sunshine duration and intensity. The minimum evaporation value in China is estimated to be 500 mm/yr, and the maximum value is 2 600 mm/yr (DU Chuan-li and LIU Xiao-dong, 2009). Compared with precipitation, evaporation is greater in western and northern areas, which exacerbates the differences in water resources in different areas. Moreover, increasing water vapor from land may lead to enhanced local convection and further changes in atmospheric circulation (Harding K J and Snyder P K, 2012; QIAN Y *et al*. 2013).

The gross amount of China's water resources is 2.80 trillion m^3. With a population of 1.3 billion people, the average water resources amount per capita is approximately 2 100 m^3, which is a quarter of the world's average level. The surface water amount is 2.68 trillion m^3, and the groundwater amount is 0.81 trillion m^3. Because of a lag in statistical data, a repeated amount of approximately 0.70 trillion m^3 is observed. Fig. 2 shows that the ratio of the population, area, arable land, GDP and socioeconomic elements are not consistent with the distribution of water resources in Northern and Southern China; these data were obtained from the China Statistical Yearbook in 2011, which was published by National Bureau of Statistics of the People's Republic of China.

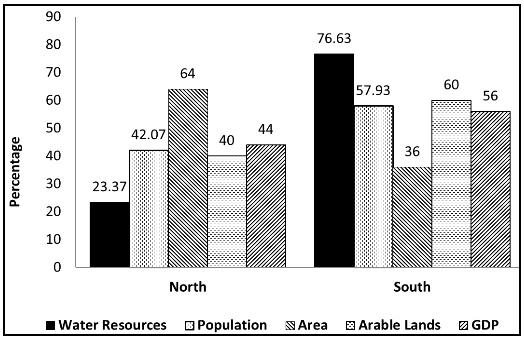

Fig. 2 Water resources and socioeconomic elements distribution in the north and south

The water resources in China present five advantages and five disadvantages. The five advantages are as follows: 1) The total amount of water resources is abundant; 2) rain and heat occur in the same period, which is beneficial to agricultural production; 3) water yield in the mountainous area is large, which is beneficial to regulation and storage; 4) several large drainage systems contribute to the allocation of national water resources; and 5) groundwater storage conditions in the North China Plain are good. The five disadvantages are as follows: 1) Average water unit area per capita is small; 2) precipitation distribution is uneven annually and interannually; 3) precipitation distribution is uneven on a spatial scale; 4) water resources are inconsistent with socioeconomic elements, such as arable lands; and 5) water resources of the Yellow River drainage basin and southwest areas are difficult to exploit.

1.1.2 Groundwater

The groundwater in China presents its own specific advantages and disadvantages. The advantages are as follows: Groundwater has a wide distribution that facilitates local utilization; groundwater is of high quality and is not easily polluted; thus, it is usually better than surface water; underground storage saves the space on the ground; and climate change has a relatively small influence on groundwater resources compared with surface water because groundwater has excellent regulation and storage capacities. However, the improper use of groundwater could cause serious environmental problems. For example, unreasonable irrigation practices cause soil salinization. Many environmental hazards are generated by groundwater overexploitation, such as saline intrusion in coastal regions, water pollution and surface subsidence. For example, in Hebei Province, the shallow water table level has dropped by 5 m to a depth of 12 m from 1983 to 1999 over large areas (HAN Z, 2003). Groundwater also plays a key role in certain engineering projects, such as mining and landslide prevention.

Groundwater is a freshwater resource that could be utilized; however, it requires a period of time to recover. Usually, the exploitation quantity of groundwater should not exceed the recharge amount. Otherwise, the ecological conditions will be worse and certain environmental hazards will occur, such as surface subsidence, drought, and rocky desertification.

A comparison of the groundwater amount for 2001-2009 with that for 1956-2000 shows that the groundwater of China has decreased by 3.6%. In the last two decades, groundwater has accounted for approximately 18% of the total water supply on a national scale according to the Water Resources Bulletin by the Ministry of Water Resources of the People’s Republic of China.

China has focused on investigating, researching, exploiting and protecting groundwater resources. The China Geological Survey (CGS) has set up the Department of Hydrogeology and Environmental Geology to organize scientists and technicians to conduct groundwater and environment investigations and research across China, and it has established a professional team of more than 50 000 scientists and technicians from the Institute of Hydrogeology and Environmental Geology (IHEG) of Chinese Academy of Geological Sciences (CAGS), the Institute of Karst Geology (IKG) of CAGS, and the International Research Center on Karst (IRCK) under the auspices of UNESCO, China Institute for Geo-Environmental Monitoring, Center for Hydrogeology and Environmental Geology, China University of Geosciences as well as provincial hydrogeological teams and geo-environmental monitoring stations. The major fields for the related work include hydrogeological and environmental geological investigations, dynamical monitoring of groundwater and its environment; the relationship between groundwater and global climate change and human activities; international transboundary aquifer research; the exploitation, utilization and protection of groundwater; and projects to address geohazards caused by groundwater. All of these related investigations and research have provided important support to the development, utilization and protection of groundwater in China and promoted international research on groundwater and associated environments.

1.2 Climate change

Global climate changes in recent decades have influence on the global water cycle and led to water resources changes in China. Precipitation and evaporation controlled by monsoon climate are two significant factors affecting the spatial and temporal variability of water resources. In terms of ocean circulation, El Nino and La Nina are the results of global climate change directly affecting the water cycle. Climate changes become an obvious trend according to meteorological studies; therefore, the El Nino and La Nina phenomena have appeared more frequently in recent years.

2 Climate changes and groundwater sustainability

2.1 Climate changes and hydrologic variability

In El Nino years, a larger amount of rainfall occurs in the rainy season in South China. In El Nino years, higher rainfall is usually accompanied by increased temperatures; consequently both precipitation and evaporation increase. La Nina years often follow El Nino years. La Nina is opposite to El Nino, and greater rainfall and higher temperatures appear in North China in summer (Wang C and Fiedler P C, 2006; GONG Dao-yi and WANG Shao-wu, 1999).

Abnormal water cycle patterns cause unusual surface water conditions. The closed hydrological connection between surface water and groundwater recharge (YAO Hui and LI Dong-liang, 1992) as well as between runoff and discharge are also changed. The hydrological factors related to groundwater that are affected by climate change include the water table, groundwater amount and leakage among aquifers, which may increase the difficulty of exploiting and utilizing groundwater.

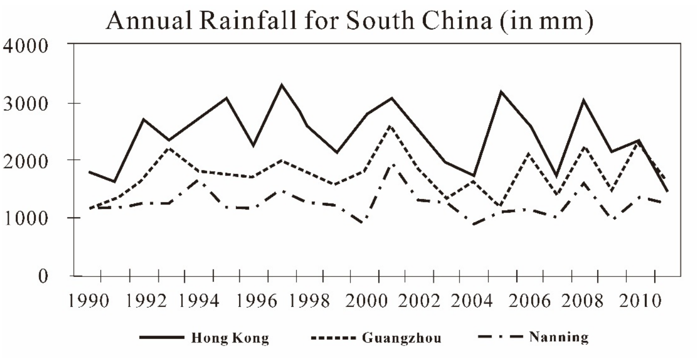

Fig. 3 (a) Annual distribution of rainfall in Guangzhou, Nanning, Guiyang and Hong Kong for the period 1990-2011

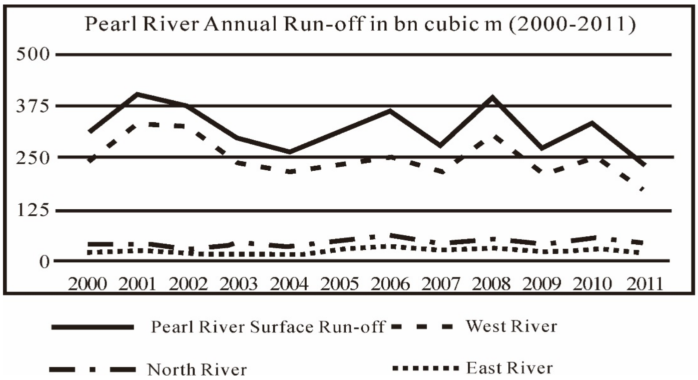

Fig. 3 (b) Annual runoff variations for the Pearl River and 3 major tributaries-West, North and East rivers

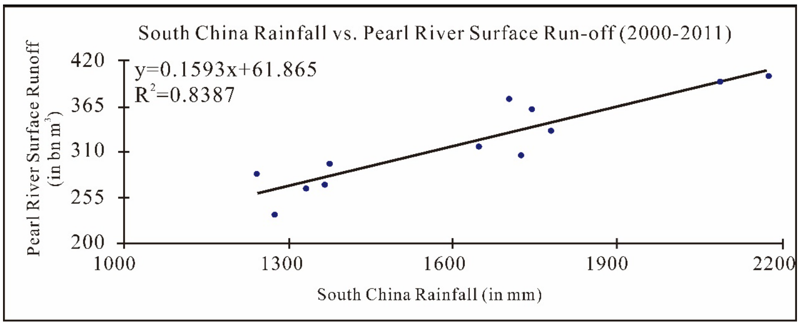

Fig. 3 (c) Plot between the Pearl River annual surface runoff and South China annual rainfall. The correlation coefficient R2=0.8387 indicates a strong positive correlation between the two variables (Lo P K P, 2014)

2.2 Impacts of climate change on groundwater

2.2.1 Predicted sustainability of groundwater resource under climate change

Groundwater is recharged via surface water infiltration and direct rainfall infiltration. Both of these processes are affected by precipitation and evaporation to a large extent. Rivers and lakes may have fissures and conduits to underground rivers. Less precipitation reduces the water in rivers and lakes and leads to insufficient recharge. Usually, water infiltrates to the subsurface through the soil layer. Climate change and variability are expected to have profound effects on soil water and temperature (Jasper K *et al*. 2006; Jungkunst H F *et al*. 2008). Precipitation must meet the soil capacity first before it reaches the aquifer. Sandström K (1995) showed that a 15% reduction in precipitation without changes in temperature resulted in a 40–50% reduction in groundwater recharge. Consequently, insufficient rainfall will reduce the infiltration recharge of groundwater. Less recharge causes less storage of groundwater. The amount of groundwater not only affects exploitation and utilization but also influences the groundwater quality. If less recharge and storage persist for a long period, then the increasingly rigid demands for groundwater resources for national economic construction will lead to overexploitation and cause continuous decreases of the water table. JIANG Dong *et al*. (1999) showed that more than 100 cities had an obvious decrease of the water table and 56 relatively large regional funnels with a total area more than 90 000 km^2 were formed. Over-exploitation of groundwater is serious in northern China, such as along the North China Plain, six basins of Shanxi Province, the Songnen Plain, and the inland basin of northwest China. In addition, excessive groundwater exploitation leads to declining terrestrial water storage, decreased stream flows, and weaker hydraulic connections between aquifers and rivers (Szilagyi J 1999, 2001; Kollet S J and Zlotnik V A, 2003; Biggs T W *et al*. 2008).

2.2.2 Major threats to water resources and the environment because of the climate change

An increasing trend of average temperature because of global climate change has led to melting sea ice and rising sea levels. In coastal areas, the risk of seawater intrusion increases with sea level rises. Because of its high salinity, seawater raises the total dissolved solubility (TDS) of groundwater and causes water quality deterioration. TDS also can rise with the groundwater shortages that threaten drinking and irrigation because of an insufficient inflow of fresh groundwater for dilution. In addition, strong evaporation can lead to soil salinization. High salinity soil will change the quality of infiltrated water and pollute the groundwater.

In El Nino years, large amounts of rainfall in the rainy season lead to floods and water logging in South China and extreme droughts in North China when the rainy season ends. These two water resource problems are caused by climate change and threaten the socioeconomic development of China. La Nina years provide floods and water logging in North China during summer. In addition, abnormal sea water temperatures in the east Pacific increase the frequency of typhoons in La Nina years. Typhoons mainly influence the rainfall in East China, thus making the water cycle more complex (ZHANG Yue-cong and MENG Xian-feng, 2005).

Because of the shortage of water resources in the North China Plain, the shallow groundwater level of Hebei Province and Beijing decreased by 20-40 m over the past 30 years. The deep groundwater of the North China Plain has already formed a regional cone of groundwater depressions crossing Hebei, Beijing, Tianjin, and Shandong. Up to 76 732 km^2 of the area was covered by below-sea level groundwater, thus accounting for 55% of the entire area of the North China Plain.

2.3 Impact of climate change on groundwater dependent systems and sectors

Water shortages and quality deterioration are the two major groundwater problems associated with climate change. These problems mainly emerge in the following three aspects: Human community, agriculture, and industry.

2.3.1 Human communities

The six great basins of Shanxi Province suffer from groundwater shortages to different degrees. From 2001 to 2006, the overexploitation of groundwater in middle basins has reached to 3.75×10^8 m^3/yr. Because of decreasing water levels, groundwater could not easily be reached in Datong and Yuncheng. The shallow groundwater of the Changzhi Basin dried up, which reduced the ability of local residents to obtain drinking water. In the inclined region of the western Songnen Plain and the low region in the middle, the phreatic water level decreased by 3-5 m on average compared with that of the 1960s and may even decrease by 3-8 m in certain places. In the exploitation area of the concentrated water supply source in the high plain of eastern Songnen Plain, the water table declined by 5-25 m. Because the groundwater has been overexploited for a long time, the groundwater has changed from confined water to unconfined interlayer water, with the water level 10-18 m lower than the aquifer roof and the yield of a single well declining by 30-50%. In the northwest areas, the groundwater level of the Shiyang River Drainage Basin has declined most dramatically. In the middle of the drainage basin, the water level decreased from 10-20 m above the overflow zone of the springs to 1-5 m below the overflow zone, which decreased the springs' flow rate, with some even drying up.

Groundwater shortages not only cause decreases in the water table but also result in land subsidence and karst sinkholes. In the early 1990s, the land subsidence area was approximately 48 700 km^2 across 16 provinces (districts, cities), including Shanghai, Tianjin, Beijing, Jiangsu, Zhejiang, and Hebei. Until 2003, the land subsidence area reached 93 855 km^2, with a serious land subsidence region composed of the Yangtze Delta, North China Plain, Fen River and Wei River fault basin (YIN Yue-ping *et al*. 2005).

The Yangtze Delta is the most serious land subsidence area in China. Shanghai has suffered from the earliest and most considerable land subsidence, which caused severe damage to the local society. In the 1920s, rapid urban construction along with increasing groundwater exploitation around the urban area caused immediate land subsidence. Thus far, the surface subsidence at over 200 mm in the Shanghai downtown area, Suzhou, Wuxi, Changzhou, and Jiaxing has covered an area of approximately 10 000 km^2, thus accounting for 1/3 of the total area, and this area is expected to be connected as a sheet. Although groundwater exploitation bans have been recently enacted and the water table in most areas is beginning to rebound, the subsidence rate is holding constant at 20-40 mm/yr and even reaches 80-120 mm/yr (Fig. 4).

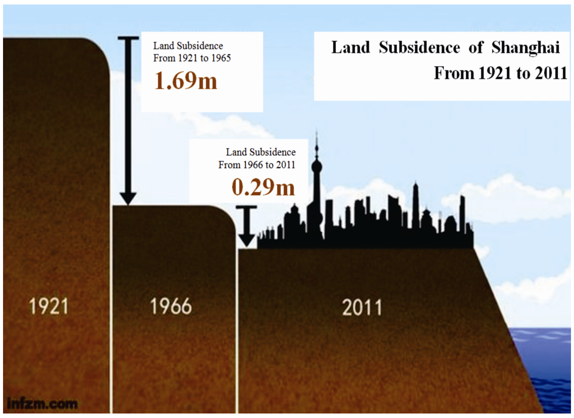

Fig. 4 Land Subsidence Model of Shanghai, China for 1921-2011 (http://www.infzm.com/content/83057?dooc)

As the largest land subsidence area in China, the area of the North China Plain experiencing subsidence is more than 70 000 km^2, with Tianjin, Cangzhou and northeast rural area of Beijing as the three centers. The land subsidence of Tianjin has occurred simultaneously with that of Shanghai since 1920s, and the deepest land subsidence is over 3.1 m, which is the deepest in China. The land subsidence of the North China Plain is connected with the west Hebei plains, which is consistent with the large cone of groundwater depression formed by groundwater exploitation.

The Fen-Wei graben developed along the Wei River and six basins in Shanxi and spread obliquely. This area experiences strong tectonic movement, with the base structure lifting and falling dramatically. Because of groundwater exploitation, land subsidence and many ground fissures spread along tectonic lines. The Xi'an area has experienced continuous subsidence at up to 2.6 m, with 13 ground fissures presenting a total length of 73 km. Taiyuan has experienced land subsidence up to 3 m, with the fissures presenting a total length of 15 km.

Karst sinkholes are a special geohazard in karst areas, which are mainly distributed in South China, Central China, Southwest China and East China. The high-risk area for karst sinkholes is approximately 600 000 km^2, which encompasses more than 30 metropolises or medium cities, such as Guangzhou, Wuhan, Shenzhen, as well as 328 counties and small cities. Karst sinkholes have shown an increasing trend over time, changing from dozens of times per year before 1980 to several hundreds of times per year currently (Fig. 5). Spatially, karst sinkholes presented urbanized and industrialized trends.

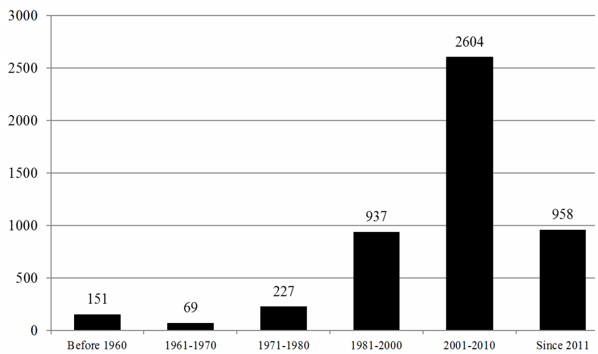

Fig. 5 Changes in the frequency of karst sinkholes in China since 1960

A majority of the karst sinkholes of China (81%) have been caused by human engineering. Groundwater overexploitation, dewatering mines, discharging, and underground engineering projects are the primary causes of karst sinkholes. For example, 97 karst sinkhole sites and 161 karst sinkholes occurred in Tailai Basin in Shandong Province. The karst sinkholes were mainly concentrated in the cone of a karst groundwater depression and the area under its influence, which are caused by the overexploitation of groundwater, which resulted in a decrease in the water table of over 10 m (WANG Yan-ling *et al.* 2015).

2.3.2 Agriculture and Industry

Although certain areas present a considerable amount of natural water resources, effectively detecting and exploiting groundwater is difficult because of the special geological conditions and geographic environment of groundwater; in addition, water conservancy projects have not developed the facilities for water storage. Engineering water shortages are common in every drainage area of China, especially in the karst mountainous areas of Southwest China, the watershed of the Yangtze River Drainage Area and the Pearl River Drainage Area.

In Southwest China, the sub-tropical monsoon climate leads to considerable amounts of precipitation that are uneven annually. Karst fissures and conduits are well-developed underground, and rainfall transiently converges on the surface and disperses and infiltrates to recharge groundwater. Rainfall is discharged to deep-cut valleys through rapid runoff, which produces dramatic dynamical changes of the karst water table and fluxes. Therefore, it is quite difficult for karst aquifers to adjust groundwater effectively, which leads to extremely uneven spatial and temporal distributions of groundwater resources. In addition, because of the rough landforms of the karst mountainous region in Southwest China and the complicated karst aquifer structures, it is very difficult to explore and develop karst water resources, both technically and economically. This region is an entirely undeveloped economic area, and the engineering water shortages have not been solved effectively.

3 Adaptation to climate changes

Prior to this century, China had not investigated and evaluated groundwater pollution throughout the country. Formerly, investigations and research into groundwater mainly focused on assessing the formation conditions and the resource amounts, with less attention focused on water quality or pollution, which may have only been investigated locally. There was no systematical investigation of groundwater quality or pollution.

From 2005 to 2016, the CGS of the Ministry of Land & Resources of China conducted national groundwater pollution investigations. The results showed that the overall groundwater quality was relatively good, although in certain regions, the groundwater was polluted severely. According to the investigation and monitoring results, the overall over-standard percentage of groundwater contamination in China is 15%, with nitrogen and metallic pollution the most serious. In addition, organic pollution is becoming more severe. Nitrogen contamination is the most serious pollution for groundwater, which is primarily from fertilizer overuse, dispersed breeding, landfills and sewage discharge. Heavy metal pollution, such as over-standard concentrations of Pb, Cr, and Hg, could also be found in certain places. These over-standard contaminants are distributed around urban areas, factories or mines. In addition, organic pollution could be detected in groundwater, including benzene serials of petrochemicals, organic chlorine solvents, and pesticides, especially in Eastern China in areas with a developed economy and inland cities with larger populations. Widespread agricultural pollution is an important cause of widespread shallow groundwater pollution.

Key issues related to groundwater pollution in China can be organized according to the following three main aspects: First, large areas are suffering from groundwater pollution; second, regional detailed data on groundwater pollution are insufficient; and third, proper experience and technology are lacking to prevent and treat groundwater pollution.

In Yunnan Province, the overall reservoir capacity only accounts for 2% of the interannual average runoff, with many existing dangerous reservoirs (WANG Yong-de, 2014). Since 2009, a number of provinces and cities, such as Yunnan, Guizhou, Guangxi, Sichuan and Chongqing, have suffered from serious droughts continuously during winter and spring, which highlighted the predominant problems, such as a lack of water sources in this region, serious engineering water shortages and a lack of water conservation facilities (LI Wei and NAN Chun-hui, 2012).

4 Challenges and problems

To address climate change, groundwater protection measures have been included in current laws and regulations; however, these measures are not sufficiently comprehensive and systematized, which produces large obstacles for implementation. Thus, these measures are not beneficial for groundwater monitoring and protection. This disadvantage is mainly reflected in the lack of comprehensive laws on groundwater resources.

A comprehensive groundwater monitoring system is fundamental to hydrogeology, engineering geology and environmental geology. Because of insufficient funding, groundwater management and maintenance are lacking. Consequently, among the tens of thousands of monitoring stations, less than half are operational. There are only 1 422 national monitoring stations that only cover 10.2% of the national territory. Areas with limited monitoring do not accurately convey the groundwater utilization in China. Supervisory departments are seriously inadequate at all levels; thus, sufficient and effective support is not provided for groundwater management. However, groundwater monitoring is a popular research topic in China, and most studies focus on 1) optimizing monitoring stations, 2) improving data reliability and 3) constructing groundwater monitoring models.

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