



Review: Safe and sustainable groundwater supply in China

Yanxin Wang¹ · Chunmiao Zheng² · Rui Ma¹

Received: 31 October 2017 / Accepted: 30 April 2018 / Published online: 14 June 2018
© Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract

Exploitation of groundwater has greatly increased since the 1970s to meet the increased water demand due to fast economic development in China. Correspondingly, the regional groundwater level has declined substantially in many areas of China. Water sources are scarce in northern and northwestern China, and the anthropogenic pollution of groundwater has worsened the situation. Groundwater containing high concentrations of geogenic arsenic, fluoride, iodine, and salinity is widely distributed across China, which has negatively affected safe supply of water for drinking and other purposes. In addition to anthropogenic contamination, the interactions between surface water and groundwater, including seawater intrusion, have caused deterioration of groundwater quality. The ecosystem and geo-environment have been severely affected by the depletion of groundwater resources. Land subsidence due to excessive groundwater withdrawal has been observed in more than 50 cities in China, with a maximum accumulated subsidence of 2–3 m. Groundwater-dependent ecosystems are being degraded due to changes in the water table or poor groundwater quality. This paper reviews these changes in China, which have occurred under the impact of rapid economic development. The effects of economic growth on groundwater systems should be monitored, understood and predicted to better protect and manage groundwater resources for the future.

Keywords China · Groundwater resources · Hydrochemistry · Groundwater/surface-water relations · Groundwater sustainability

Introduction

Groundwater resources are critical for economic development and potable water supply, and groundwater supply accounts for 17.5% of the total water supply in China (Ministry of Water Resources of the People's Republic of China 2015). According to the National Groundwater Pollution and Control Plan (2011–2020), 65% of domestic water consumption, 50% of industrial water consumption and 33% of agricultural water consumption in the northern area of China depend on groundwater. Groundwater extraction has increased by approximately

2.5 billion m³/year to meet agricultural, industrial and domestic needs over the past few decades (Ministry of Ecology and Environment of the People's Republic of China 2011). Consequently, groundwater levels have dropped greatly in many areas. As a result, 240 depression cones have formed, which occupy an area of 7×10^4 km² in the eastern part of the North China Plain (location is shown in Fig. 1). Water scarcity has become an increasingly serious problem for most of the 660 cities in China (Qiu 2010). In particular, the successive decrease in the groundwater level in many areas has led to groundwater reservoirs being depleted at an alarming rate in the northern and northwestern regions of China (Qiu 2010).

China has also been faced with groundwater quality problems due to enrichment with contaminants of either anthropogenic or geogenic origin. The Chinese hydrogeochemical investigation reported by the China Geological Survey (Wang et al. 2016c) showed that groundwater quality is better in southern China than it is in northern China, and that it is better in mountainous areas than in basins, in pediment plains than in coastal areas, and in deep aquifers than in shallow ones. The detected chemical components that mainly affect the groundwater quality in China are Fe, Mn, total hardness, SO₄, F, total dissolved solids (TDS) and arsenic (As), among others. High

Published in the special issue “Groundwater sustainability in fast-developing China”

✉ Yanxin Wang
yx.wang@cug.edu.cn

¹ State Key Laboratory of Biogeology and Environmental Geology & School of Environmental Studies, China University of Geosciences, Wuhan 430074, People's Republic of China

² School of Environmental Science and Engineering, South University of Science and Technology of China, Shenzhen 518055, People's Republic of China

Fig. 1 A map of China showing the locations mentioned in the ‘Introduction’



SO₄ and TDS components in the eastern coastal plains mainly originate from millions of years of seawater intrusion; 26% of groundwater supply sites are at risk of their conventional water quality parameters exceeding the national water quality standard in northwestern China; and in southern China, shallow groundwater tends to be acidified, especially in the Pearl River delta (Lin and Wang 2017; location is shown in Fig. 1). In southern and southeastern China, where the economic growth rate has been great, groundwater has been widely contaminated with heavy metals and other pollutants such as persistent organic contaminants. In other places, such as northwestern China where water scarcity has been most serious, groundwater contamination has also been widely reported.

To adjust the uneven distribution of water resources and alleviate groundwater depletion, large-scale water conservancy projects have been implemented across China. Particularly important among them is the South-to-North Water Diversion Project (SNWT) (Fig. 1), with which the government plans to

reduce groundwater use in Tianjin, Beijing and Hebei provinces to 65% of their current levels by 2023 (Qiu 2010). However, the construction and operation of water conservancy and transfer projects can significantly change the groundwater flow system and affect groundwater quality.

As a result, changes in groundwater flow and quality have caused serious ecological and geo-environmental problems in China, such as drying of springs (Sun et al. 2016c), decreases in river base flow (Wang et al. 2001), vegetation degradation (Jia and Ci 2000; Jia and Xu 1998), soil and groundwater salinization (Brunner et al. 2008; Tang and Zhang 2011; Sun et al. 2016b), land subsidence (Hu et al. 2004; Ma et al. 2006) and desertification (Ge et al. 2016; Li et al. 2015; Liu et al. 2016a). The demand for water grows as China's economy develops fast. Thus, studies of groundwater sustainability and its ecological and geo-environmental effects are urgently required. This paper reviews the state-of-the-art changes in groundwater quantity

and quality in China that have occurred under the impact of rapid economic development, as well as their ecological and geo-environmental effects, and stresses the importance of effective governance of groundwater resource management to ensure the ultimate goal of safe and sustainable supply of groundwater in China.

Changes in groundwater dynamics

Groundwater resource depletion

According to the assessment of Zhang et al. (2006), groundwater resources are unevenly distributed in China; 67.7% of these resources are located in southern China and only 32.3% are located in northern China. However, the extent of groundwater exploitation in northern China is much more intensive than that in southern China (Lin and Wang 2017). The groundwater supply holds 30% of the total water supply in more than 400 cities. Among the total of 657 cities in China, more than 400 (61%) cities use groundwater as their major water supply. In rural areas of China, people generally use groundwater as their drinking water source, and 40% of the total farmland is irrigated by groundwater. In northern regions, groundwater is the source for 65% of domestic water, 50% of industrial water and 33% of irrigation water supply (Ministry of Environment Protection 2011). The exploitation of groundwater has facilitated a steady increase in grain production. All of these data indicate that China's economic development and people's livelihoods depend greatly on groundwater. With rapid economic development and population growth over the past three decades, groundwater exploitation in China has increased dramatically. Since the 1970s, the total amount of groundwater exploitation has increased at an average rate of 2.5 billion m³/year from 57 billion m³/year in the 1970s, to 75 billion m³/year in the 1980s, and further to 110 billion m³ by 2015, accounting for nearly 18% of the total water supply (Ministry of Water Resources 2015). Agricultural water use accounts for the largest percentage of total groundwater use, although it has decreased from 88% in the 1980s to 62% in the late 1990s; and industrial and municipal water use has increased from 12% in the 1980s to 38% in the late 1990s. This trend will likely continue to keep pace with the acceleration of industrialization and urbanization.

As the groundwater abstraction rate has increased, most aquifers in northern China have been over-exploited; among these, the aquifers throughout the entire Hebei Province and those in mega- or medium-sized cities such as Beijing, Tianjin, Shenyang, Haerbin, Jinan, Taiyuan and Zhengzhou are all over-pumped. More than 100 regional groundwater depression cones have been formed, with a total area exceeding 150,000 km². In the North China Plain, the depression cones range from Hebei to Beijing, Tianjin, and Shandong, with

groundwater levels that are lower than sea level in an area of 70,000 km² (Liu et al. 2001). Similar to other places around the world, groundwater resources are mainly consumed by pumping for irrigation in China, where the conflict between securing food production and maintaining sustainable groundwater use is currently being intensified (Cai and Ringler 2007; McLaughlin and Kinzelbach 2015). Based on the inventory constructed by Werner et al. (2013), three cases from China were ranked in the top 10 groundwater mega-depletion cases around the globe. Problems regarding groundwater over-extraction have occurred in more than 164 locations in 24 of the 31 provinces in China, and they have affected an area of more than 180,000 km² (Wang et al. 2007). Previous studies of groundwater depletion due to overdraft in China have consistently focused on the North China Plain (NCP; Gorelick and Zheng 2015; Zheng et al. 2010). This is because the NCP is considered to represent one of the most serious cases of large-scale aquifer over-exploitation, as its water tables have dropped continuously at a rate of 0.5–2 m/year over the past 60 years. The current water table is estimated to be as low as 120 m below land surface in some places, and deep cones of depression have formed in heavily exploited areas (Cao et al. 2015; Pei et al. 2015). For these reasons, the NCP (Hai River Basin) is ranked as number 1 in Werner's list among all mega-depletion cases using a severity index (Werner et al. 2013). Although the groundwater storage depletion rate differs among different researchers (Table 1), it has been commonly agreed that the NCP is one of the regions in the world with the most serious problems of groundwater storage depletion (Aeschbachhertig and Gleeson 2012). The NCP plays an important role in China's food production and is the home to more than 200 million people. Fast-growing groundwater exploitation is the lifeblood that has been needed to sustain agricultural production in the NCP over the past several decades. However, the sustainability of this production appears to be threatened by a widespread decline in groundwater level, which has locally reached rates of more than 1 m/year (Liu et al. 2008). From 1900 to 2000, approximately 130.3 km³ of the net cumulative depletion of groundwater occurred in the NCP, which is equivalent to a sea level rise of 0.361 mm. This number increased by approximately 31% over the next 8 years after 2000 to reach a cumulative total of approximately 170.3 km³ (Konikow 2011). The main cause of this depletion is the excessive extraction of groundwater for irrigation where groundwater is slowly renewed; climate change has the potential to exacerbate this problem in some regions.

Recharge and discharge processes under the impact of intensive human activities

Intensive human activities have greatly affected the processes of groundwater recharge and discharge. Among them, the

Table 1 Results of groundwater storage depletion-rate studies in the NCP

Location	Area	Period	Method	Groundwater storage depletion rate	References
North China	370,000 km ²	2003–2010	GRACE	8.3 ± 1.1 km ³ /year (2.2 ± 0.3 cm/year)	Feng et al. 2013
NCP (the Piedmont Plain)	54,000 km ²	2003–2013	GRACE	4.65 ± 0.68 cm/year	Huang et al. 2015
NCP (East Central Plain)	86,000 km ²	2003–2013	GRACE	1.69 ± 0.19 cm/year	Huang et al. 2015
NCP	140,000 km ²	1970s	Groundwater modeling	~1.78 cm/year	Cao et al. 2015
		1980s		~2.86 cm/year	
		1990–1996		~1.43 cm/year	
		1997–2001		~5.0 cm/year	
		2002–2008		~2.86 cm/year	

impacts of widespread irrigation, soil conservation strategies and water diversion projects have been well studied.

Irrigation activities have had large-scale impacts on groundwater systems by changing both recharge and discharge processes (Döll et al. 2012; Rohden et al. 2010). Recharge has raised the water table as a result of irrigation, while increased pumping has offset the higher recharge rates and resulted in water-table declines (Kinzelbach et al. 2003; Scanlon et al. 2006). In China, this large-scale redistribution of freshwater from rivers, lakes and groundwater to arable land has led to both groundwater depletion in regions with primarily groundwater-fed irrigation (Yang et al. 2015) and groundwater accumulation as a result of recharge from the return flows from surface-water-fed irrigation (Döll et al. 2012; Wang et al. 2015a). Kendy et al. (2004) used North China as an example and found that the areal recharge represents a fraction of precipitation and irrigation and that this fraction increases with increasing precipitation and irrigation. Improving irrigation efficiency and reducing groundwater pumping for irrigation have had no effect on water-table declines due to reduced seepage (Kendy et al. 2004).

Soil conservation approaches also have great impacts on deep drainage. Structural soil conservation strategies such as gully sites are consistent with deep drainage, while ecological soil conservation strategies such as mature tree and shrub plantations may prevent deep drainage (Gates et al. 2011). Thus, structural soil conservation strategies or less water-intensive vegetation could be more practical and sustainable for arid and semiarid areas.

Water diversion projects have also been reported to greatly affect groundwater flow regimes. The effect of SNWT on groundwater systems is currently minor. Yang et al. (2012b) used numerical modeling to predict groundwater flow; their results showed that the areas of cones of depression will be reduced by different degrees. Ye et al. (2015) applied a large-scale surface-water/groundwater distribution hydrological model to assess the impact of the central route of the SNWT on groundwater. Their results indicated that the SNWT will only decrease the rate of groundwater level decline and cannot fully resolve the water resource crisis in the Hai River Basin

and that the region of groundwater overexploitation will decrease by approximately 20%. The Heihe River Basin is the second-largest inland river in northwestern China, and it is characterized by typical arid and semiarid areas. The Heihe River is the primary recharge source for the groundwater in the lower reaches. In recent years, the decreased river runoff due to overexploitation in the middle stream has caused the groundwater level to decline in the lower part. To address this issue, a water diversion project from the middle to lower stream was implemented to save the downstream ecosystems in 2000 (Cheng et al. 2014). A similar situation also occurred in another endorheic river basin in China, namely, the Tarim River Basin. Since 2000, eight water diversions from the upper stream and the neighboring Kaidu-Kongque River have been implemented to save the ecosystems in the lower Tarim River (Huang and Pang 2010). The water diversion projects in the endorheic river basins have led to more intensive groundwater use in the middle stream but less groundwater replenishment due to decreased river leakage in the lower stream (Aishan et al. 2013; Schilling et al. 2014; Wang et al. 2015a).

Other human activities such as mining, can also change groundwater recharge and discharge. Wastewater drainage from mining will lead to changes in groundwater recharge, runoff and discharge in regional groundwater systems, which will further cause groundwater depletion (Lin and Wang 2017).

Spatial-temporal changes in groundwater flow regimes

In the long run, land-use change and climate change are the two main factors affecting spatial and temporal changes in groundwater flow regimes, both directly (through replenishment by recharge) and indirectly (through changes in groundwater use) (Taylor et al. 2013).

Land-use change

Land-use changes such as revegetation and agricultural land expansion and urbanization, can result in changes in both drainage and evapotranspiration rates, thus affecting natural

groundwater replenishment. Guo et al. (2015) attributed land-use changes to decreased flow in 37 of the 45 springs in a karst aquifer in southern China since 1990 (Guo et al. 2015). The impacts of land-use changes on the groundwater system in the middle reaches of Heihe River Basin from 1969 to 2000 were analyzed from the perspective of the groundwater recharge and discharge system. Caused by land-use change, the groundwater recharge decreased by $2.168 \times 10^8 \text{ m}^3/\text{year}$ from 1970 to 1985 and increased by $0.134 \times 10^8 \text{ m}^3/\text{year}$ from 1986 to 2000; the groundwater discharge decreased by $2.035 \times 10^8 \text{ m}^3/\text{year}$ and increased by $0.6785 \times 10^8 \text{ m}^3/\text{year}$, respectively (Wang et al. 2005).

In the southern Horqin Sandy Land, northeastern China, the effects of land-use changes on the water table from 1953 to 2009 were investigated. The results indicated that the use of Mongolian pine plantations to prevent expansion of sandy land has effectively improved local environmental conditions, leading to the expansion of more water-consuming agricultural land and broadleaved forests, which has changed the water balance and continuously decreased the water table (Zheng et al. 2010). Since 1952, China has implemented a large-scale tree planting program in the country's arid regions to combat desertification; however, many studies have shown that there is a high risk that this program will exacerbate water shortages and lower the water table (Lu et al. 2016).

Urbanization introduces impervious surfaces, and urban pipelines can reduce water discharge to underground reservoirs (Hua et al. 2015). Jiao et al. (2006) studied the impact of land reclamation and urbanization on the regional groundwater regime in Hong Kong (Jiao et al. 2006). Large-scale land reclamation significantly reduced submarine groundwater discharge (SGD) and thus lifted the groundwater level, which increased the risk of flooding. Meanwhile, the deeper foundations of new architectures and denser underground transportation system decreased the overall permeability and retarded the flow of the groundwater system.

Climate change

Climate variability and change are primarily related to the distribution of precipitation and directly determine the recharge rate. Hao et al. (2006) found that the karst aquifers at the Liulin Springs responded remarkably to climate change rather than human activities and, in particular, responded to changes in precipitation input (Hao et al. 2006). Moreover, climate change may induce more extreme hydrological events (e.g., droughts and floods). Although there is little change in annual precipitation, the temporal distribution of peak flow days and low flow days also has a profound impact on groundwater systems (Zhou et al. 2011).

At high latitudes and elevations, global warming changes the spatial and temporal distribution of snow, ice and permafrost and thus affects groundwater dynamics. Permafrost has

been reduced by approximately 18.6% from $2.15 \times 10^6 \text{ km}^2$ in the 1970s to $1.75 \times 10^6 \text{ km}^2$ in 2006 due to climate change and human activities (Cheng and Jin 2012). Previous studies of the linkage between permafrost and groundwater on the Qinghai-Tibet Plateau (QTP) and in northeastern China have shown that groundwater exhibits marked seasonal variability corresponding to cold and thaw seasons. Meanwhile, the lowering of water tables has been observed in permafrost areas in the QTP, mainly because the thawing permafrost opened channels in the permafrost aquitard and caused the following downward flow of supra-permafrost groundwater (Cheng and Jin 2012). For a more quantitative analysis, more detailed investigations, experiments, and long-term monitoring and observations on various spatiotemporal scales are still necessary.

Geogenic groundwater quality problems

High-arsenic groundwater

In China, there are some of the most populated regions at risk of exposure to geogenic high-arsenic (As) groundwater. However, current estimates of the Chinese population exposed to elevated As concentrations vary widely, ranging from 0.58 million (Yu et al. 2007) or 1.85 million (He and Charlet 2013) to as many as 19.6 million individuals (Rodríguezlazo et al. 2013). China is a typical high-As groundwater ($>10 \text{ } \mu\text{g/L}$) region, where 19 of the 34 provinces in the mainland have high-As groundwater (Guo et al. 2014a), including Anhui, Beijing, Gansu, Guangdong, Hebei, Henan, Hubei, Inner Mongolia, Jilin, Jiangsu, Liaoning, Ningxia, Qinghai, Shandong, Shanxi, Shaanxi, Sichuan, Xinjiang, and Yunnan (Fig. 2).

Geographically, there are two types of geogenic high-As groundwater areas: fluvial/alluvial-lacustrine plains of humid or semi-arid/arid regions and the river deltas of humid regions (Guo et al. 2014a). The former mainly includes the Jiangnan Plain of the Yangtze River in the humid climate areas of central China, and the basins and plains of the Yellow River and the Haihe River in the arid regions of North China such as the Hetao Basin, the Huhhot Basin, the Yinchuan Basin, the Datong Basin, the Yuncheng Basin, the Songnen Basin, the Guide Basin and the Dzungaria Basin (Guo et al. 2008). The river deltas with geogenic high-As groundwater mainly include the Pearl River Delta, the Yangtze River Delta (YRD) and the Yellow River Delta.

High-As groundwater mainly occurs in shallow Quaternary sedimentary aquifers with alluvial lacustrine or lacustrine sediments in inland plain areas. In comparison, in river delta regions, high-As groundwater mainly occurs in fluvial-marine sedimentary aquifers that have been affected by transgression. In both inland plains and river deltas, high-As groundwaters, which mainly form under reducing conditions, are

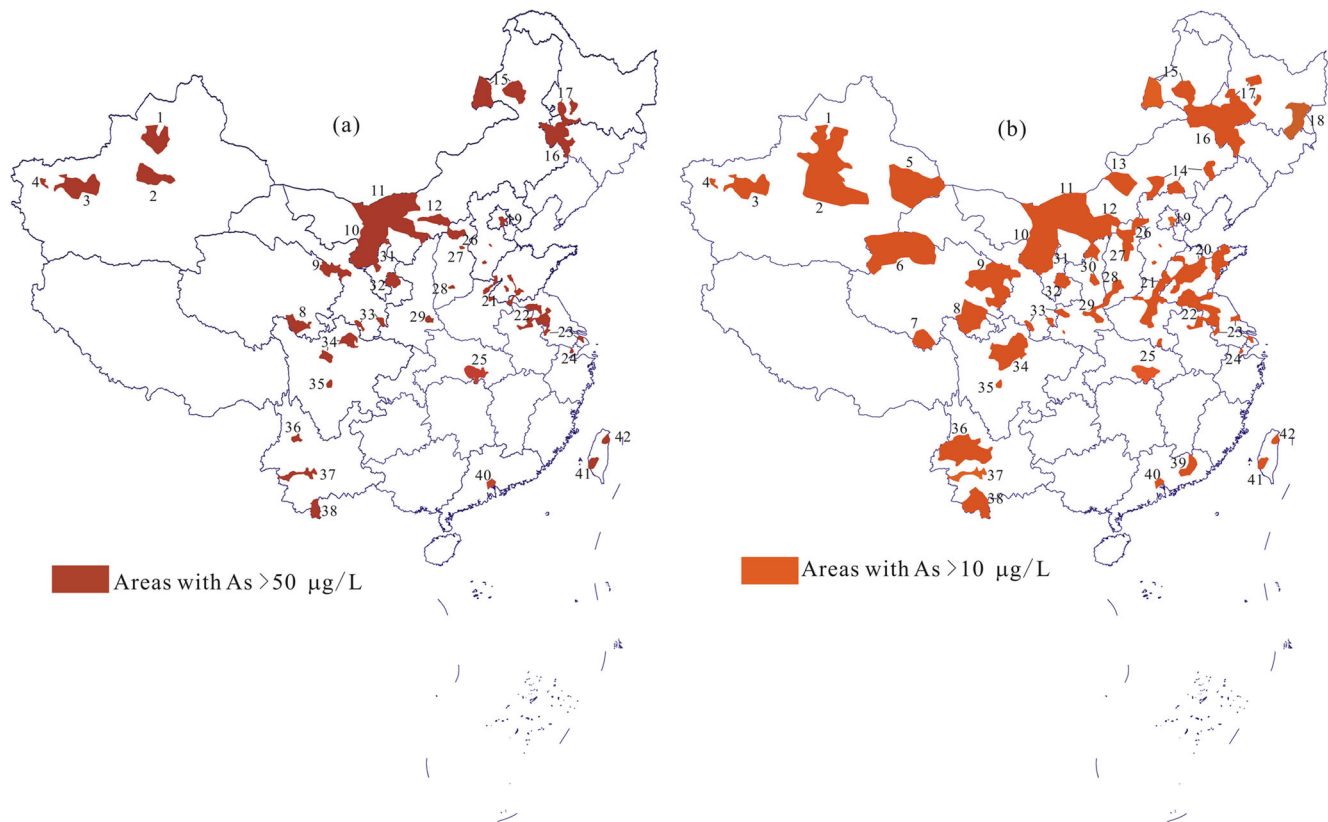


Fig. 2 Distribution of high-As groundwater in China: **a** groundwater As concentration $> 50 \mu\text{g/L}$; **b** groundwater As concentration $> 10 \mu\text{g/L}$. The numbers show the locations of As-affected areas. XIJIANG: 1 The Dzungaria basin; 2 Luntai, Bohu, and Weili counties; 3 Awati and Bachu counties; 4 Shule county; 5 Hami county; 6 Delingha county. QINGHAI: 7 Nangqian county; 8 Gande, Maqin and Dari counties; 9 Guide, Zeku, Tonren, Xunhua, Hualong, Jianzha, Gonghe, Huangyuan, Haiyan, Pingan, Huzhu, Datong, Mengyuan, and Tianzhu counties. INNER MONGOLIA: 10 Alashanzuoqi; 11 The Hetao basin, Wulatehouqi, Wulatezhongqi; 12 The Huhhot basin; 13 Shuniteyouqi; 14 Zhenglanqi, Weichang county, Naimanqi; 15 Xinbaerhuyouqi and Ewenkezuzizhiqi. JILIN: 16 The Songnen basin. HEILONGJIANG: 17 Fuyu, Lindian, Anda, Suihua, and Beian counties; 18 Jidong, Linkou, Muling and Ningan counties. BEIJING: 19 Tongzhou and Shunyi. SHANDONG: 20 The alluvial plain of the Yellow River of Shandong. HENAN: 21 The alluvial plain of the Yellow River of Henan. ANHUI AND

JIANGSU: 22 The Huai River alluvial plain. JIANGSU AND SHANGHAI: 23 The Yangtze River delta. ZHEJIANG: 24 The Qiantang River delta. HUBEI: 25 The Jiangnan alluvial plain of the Yangtze River. SHANXI: 26 The Datong basin; 27 The Taiyuan basin; 28 The Yuncheng basin. SHAANXI: 29 The Weihe alluvial plain; 30 Yan'an and Yulin counties. NINGXIA: 31 The Yinchuan basin. GANSU: 32 Huanxian county; 33 Weixian, Zhouqu, and Baoji counties. SICHUAN: 34 Shongpan, Xiaojin, Jinchuan, and Maerkang counties; 35 Luding county. YUNNAN: 36 Tengchong, Lianghe, Yunlong, Eryuan, Binchuan, Mouding, Chuxiong, Nanjian, Changning counties; 37 Gengma and Zhenyuan counties; 38 Mengla, Jinghong, Menghai, and Simao counties. GUANDONG: 39 Zhijin, Wuhua, Xingning counties; 40 The Pearl River delta. TAIWAN: 41 The Choushui alluvial plain and Chianan alluvial plain; 42 The Lanyang alluvial plain. (modified from Guo et al. 2014a)

characterized by high concentrations of Fe, Mn and HCO_3^- , high pH, and relatively low NO_3^- and SO_4^{2-} concentrations (Guo et al. 2014a). In general, the oxidation mechanism of pyrite is widely used to explain the formation of high-As groundwater. This occurs when Fe(III) oxides undergo reductive dissolution under anaerobic conditions (Tufano and Fendorf 2008), leading to As desorption and enrichment in the aqueous phase.

The main source of groundwater As is the release of solid As from aquifer sediments via (bio)geochemical processes (Guo et al. 2014a). In inland basins of arid regions, the chemical composition of high-As groundwater is not only affected by water–rock interaction processes but also by evaporation. Organic-rich deposits and alkaline waters have been

reported to cause As desorption from the solid phase (Schaefer et al. 2016). In river delta regions, the salinity of groundwater is normally low due to the large amount of precipitation and recharge (Jia and Guo 2013). The interlayers of marine and fluvial deposits in river deltas mainly comprise silty sand, silt, clayey silt and clay, with high contents of natural organic matter. These conditions, together with low groundwater flow rates, readily lead to reducing conditions in aquifers (Guo et al. 2014a). High As concentrations in groundwater are the result of the redox processes, microbially mediated reduction, and desorption processes that occur in aquifer systems. Under reducing conditions, both the reductive dissolution of Fe oxides and the reductive desorption of As are believed to occur in aquifer systems, leading to As

mobilization. Microbes, which are fueled by organic matter in aquifers and can catalyze the reduction of Fe oxides and As(V), play an important role in As mobilization (Guo et al. 2014a).

Geothermal groundwater also contains high As concentrations. In the Guide Basin and the Tengchong area, high-As groundwaters are closely associated with deep geothermal water. Usually, deep geothermal water recharges shallow groundwater via faults due to recent tectonic movement. The spatial distribution of As concentration is generally consistent with the occurrence of tension faults.

In China, groundwater contamination by geogenic As has been reported to be more serious than that of anthropogenic As (Smedley et al. 2003), which is related to mining (Wei 1992), irrigation (Norra et al. 2005) and pesticide usage (Alam et al. 2015). The interaction between groundwater and surface water was also proposed to be an important factor controlling As concentration dynamics in groundwater (Schaefer et al. 2017; Schaefer et al. 2016).

High-fluoride groundwater

China, which is one of the countries that has been most affected by high-fluoride (F^-) groundwater (Ayoob and Gupta 2006; Jadhav et al. 2015), reported in 2015 that over 70 million people have been exposed to endemic fluorosis due to their long-term intake of high- F^- water (>1.0 mg/L, Chinese guideline value; National Health and Family Planning Commission of China 2016). This situation is more severe in arid and semiarid areas, where groundwater is the main source of drinking water (Ren et al. 1996; Shen et al. 2010; Zhao et al. 2007). The F^- concentrations in cold groundwater samples in northern China range from 0.1 to 22 mg/L, and most of them are <8 mg/L (Fig. 3). Except in a few areas such as the NCP, high- F^- groundwater in China mainly occurs at shallow depths (<100 m), especially at depths of <50 m (Fig. 3). Based on its genesis, the geogenic high- F^- groundwater of China can be basically classified into three types (Fig. 3): (1) shallow high- F^- groundwater in the plains and intermountain basins of arid and semiarid areas; (2) deep high- F^- groundwater in the depositional plains and basins of arid and semiarid areas; and (3) high- F^- geothermal water (Liu et al. 1980, Ren and Jiao 1988, Wen et al. 2013).

Shallow high- F^- groundwater is mainly distributed in the subsiding basins and plains of northern China (e.g., western Songliao Plain, Inner Mongolia, inland basins of Shanxi and Shaanxi), northeastern China (e.g., Tarim Basin, Junggar Basin, Qiadam Basin and Hexi Corridor) and central China (e.g., the area from the Qinling Mountains to the Huai River; He et al. 2010; Liu et al. 1980; Ren and Jiao 1988; Wang et al. 1999; Wen et al. 2013). High- F^- groundwater is mainly distributed on a regional scale in semiarid and arid northern China. In comparison, it tends to occur on a local scale (<100 km²) in semi-humid and humid southern China (He et al. 2008; Wang et al.

1999; Wen et al. 2013). Shallow high- F^- groundwater is usually found on the front edges of piedmont alluvial fans and in the central regions of basins and plains, which are characterized by low flat terrain and sluggish groundwater flow (He et al. 2010; Ren and Jiao 1988; Wen et al. 2013). Geogenic F^- in groundwater is ultimately derived from fluorine-bearing minerals (e.g., fluorite, apatite, amphiboles and micas) in rocks and sediments (Ali et al. 2016). The host rocks and sediments of basins and plains in northern China often have high fluorine contents (Ren and Jiao 1988; Wang and Cheng 2001)—for example, the average fluorine contents of rocks, loess and sediments (0–200 cm) in the Datong Basin are approximately 666, 895 and 560 mg/kg, respectively, which are much greater than the background fluorine content of soil in China (478 mg/kg; Li et al. 2014d; Pan et al. 2013; Zhao et al. 2007). Water–rock interactions are primarily responsible for the release of F^- to groundwater, and evapotranspiration promotes F^- enrichment in shallow groundwater, especially in northwestern China (Vithanage and Bhattacharya 2015; Gao et al. 2007; Wang et al. 2009; Zhang et al. 2013a). Agricultural and industrial activities could be important sources of F^- in groundwater because some commonly used fertilizers and pesticides in China contain high contents of F^- (i.e., up to 1,161 mg/kg; Luo et al. 2017).

The high F^- concentration in deep groundwater in the coastal plains of the Bohai Sea and Yellow Sea such as the eastern NCP is mainly derived from palaeo-seawater (Ren and Jiao 1988; Wan et al. 2013), and that in the inland basins of central Shanxi and arid northwestern China such as the Tarim Basin, Junggar Basin and Chaoshui Basin may originate from palaeo-brine (Currell and Cartwright 2011; Currell et al. 2010). The Na-dominant, neutral to alkaline conditions of deep groundwater in these areas also favor F^- enrichment. Anthropogenic activity also affects the F^- distribution in groundwater. As observed in Cangzhou City in the NCP, the center of high- F^- deep groundwater is located directly in the depression cone created by groundwater withdrawal, and the average F^- concentration in the depression area gradually increased from 3.0 mg/L in 1970 to 5.1 mg/L in 2000 (Kong et al. 2015; Wang et al. 2011). These studies indicated that decreasing the head pressure in deep aquifers results in clay compaction, releasing F^- from clay into the groundwater (Kong et al. 2015; Wang et al. 2011). The downward vertical hydraulic gradient developed by exploitation further promotes the leakage of shallow groundwater with high F^- concentrations, which likely facilitates F^- enrichment in the deep groundwater of the Yuncheng Basin (Currell et al. 2011; Currell et al. 2010; Gao et al. 2007).

Geothermal groundwater, which has been widely exploited in China (Zhu et al. 2015a), generally contains high F^- concentrations. The F^- concentrations in 90% of the geothermal water samples from both high- and medium-low-temperature geothermal systems are greater than 2.0 mg/L. Extensive water–rock interactions, enhanced by higher temperatures, are the major source of F^- in most geothermal fluids

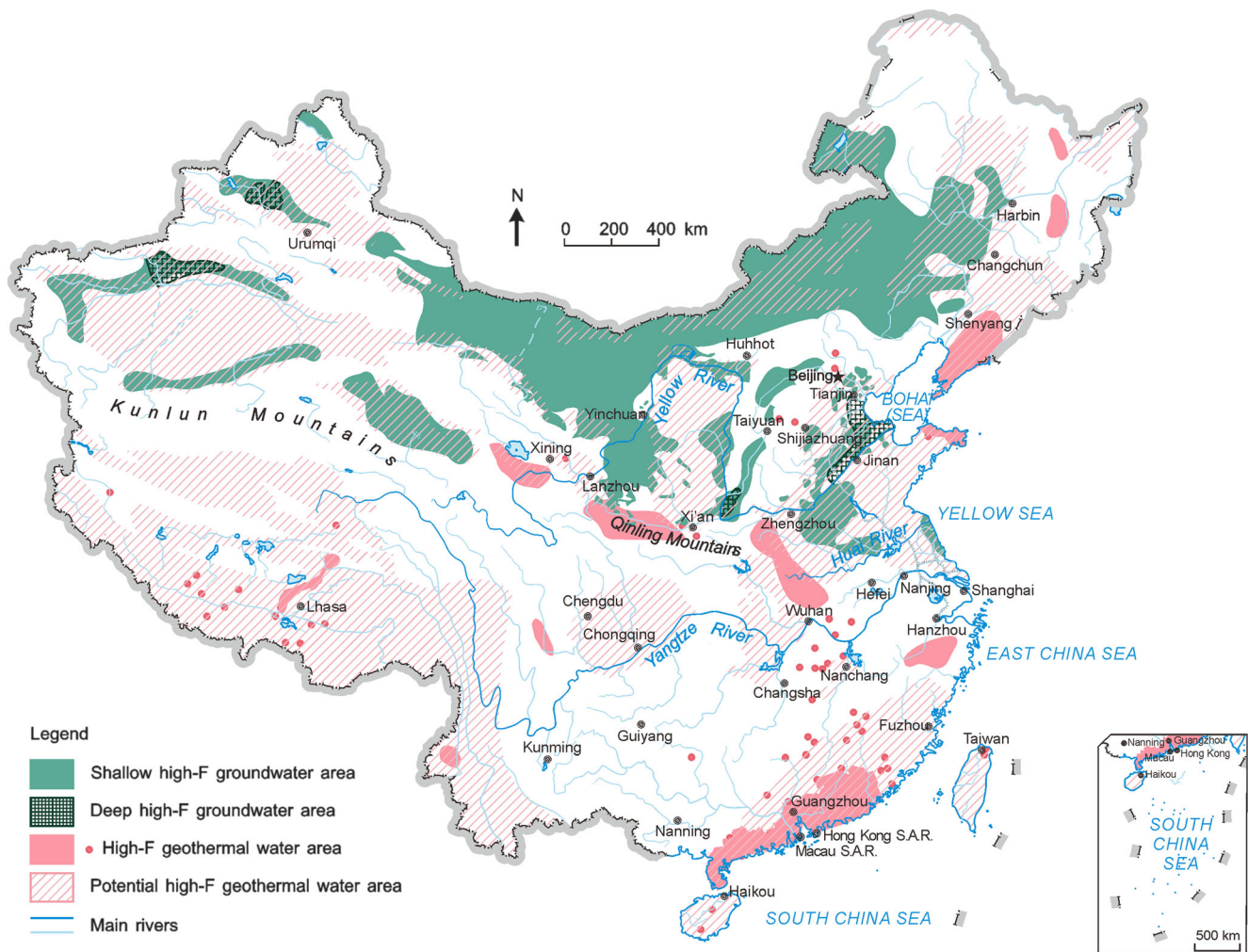


Fig. 3 Distribution of F^- in groundwater of China, modified from original maps in Long et al. (2015), Ren and Jiao (1988), Tan (1989) and Wen et al. (2013)

(Guo et al. 2017), while magmatic degassing might contribute to F^- in high-temperature magma-heated geothermal systems such as Yangbajing and Rehai (Guo 2012; Guo and Wang 2012; Sracek et al. 2015). F^- concentrations vary dramatically in geothermal systems with different reservoir lithologies. Geothermal water samples from granite and metamorphic rock reservoirs generally contain much higher F^- contents (usually >5.0 mg/L, up to 28.5 mg/L), with average concentrations of 11.3 and 13.4 mg/L, respectively, whereas in clastic rock and carbonate reservoirs, almost all geothermal water samples have F^- contents of <5.0 mg/L, with average concentrations of 2.5 and 1.7 mg/L, respectively. These differences are likely due to the different fluorine contents of diverse host rocks and water-rock interaction without the addition of magmatic fluid (Guo et al. 2009, b).

High-iodine groundwater

Geogenic high-iodine (I^-) groundwater has been found in 12 provinces in China, including Beijing, Tianjing, Hebei, Henan,

Shandong, Shanxi, Inner Mongolia, Xinjiang, Jiangsu, Anhui, Fujian and Shan'xi (Zhang et al. 2010). These cities are mainly located in the ancient flood areas of the Yellow River and the coastal areas of the Bohai Sea, arid inland basins, the YRD and the Pearl River Delta (Fig. 4). Shen et al. (2011) reported that there are 488 towns with high- I^- groundwater and 246 towns with endemic goiter cases in the areas that use high- I^- groundwater as drinking water; thus, high- I^- groundwater affects a population of over 30 million people (Shen et al. 2011).

The high I^- concentrations in groundwater are mainly controlled by the dissolution of I^- -containing minerals, the evaporation of shallow groundwater and the release of I^- in sediments in organic-rich reducing environments. High- I^- groundwater often occurs in discharge areas or areas with sluggish groundwater flow (Lin and Wang 2017). Previous studies of high- I^- groundwater have mainly focused on northern inland basin areas such as the Datong Basin, Taiyuan Basin and NCP.

Groundwater I^- concentrations ranged from 0.02 to 4,117 $\mu\text{g/L}$ in the Taiyuan Basin, and 687 out of 950

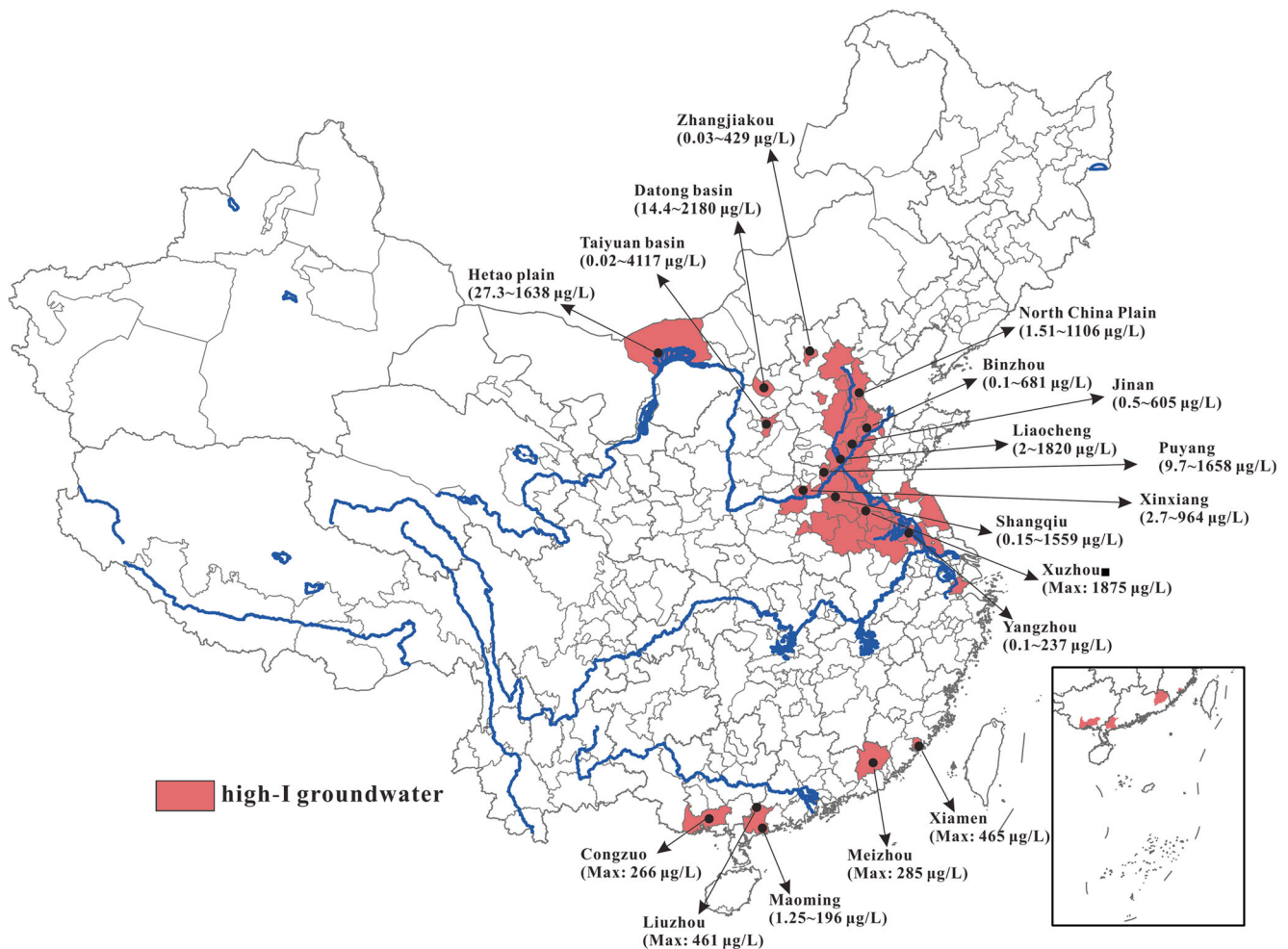


Fig. 4 Distribution of high-iodine groundwater (>150 µg/L) in China. The data used to plot this map were collected from Hua et al. (2007), Jiao et al. (2013), Li et al. (2013), Li et al. (2012), Liang and Ren (2005), Liu

(2009), Lu et al. (2011), Mo and Huiqing (2005), Su et al. (2006), Tang et al. (2006), Xie et al. (2005), Xu et al. (2012) and Zhao et al. (2014)

groundwater samples had Γ concentrations that were higher than 150 µg/L, which is the recommended guideline for drinking water established by the Chinese government (Tang et al. 2013). At Taiyuan, deeper groundwater generally had higher Γ concentrations than shallower groundwater (Tang et al. 2013). The Γ concentrations in groundwater from the Datong Basin ranged from 14.4 to 2,180 µg/L, and high- Γ groundwater mainly occurred in the central part of the basin. Vertically, both shallow and deep groundwater had high Γ concentrations (>150 µg/L). An increasing trend of groundwater Γ from 17.5 to 934 µg/L was observed along the groundwater flow path in the Datong Basin. The sediments with high total organic carbon (TOC) contents generally had high Γ contents, thus suggesting that OC-rich clayey sediments might represent the primary source of iodine. In the groundwater discharge area of the Datong Basin, when the biodegradation of sediment organic matter occurred, the Γ that was sorbed on the clayey sediment was mobilized into aqueous phases during the degradation of Γ -rich organic matter (Li

et al. 2014a). Iodide, which is the major iodine species in the reducing environment of the Datong Basin, is difficult to re-incorporate into previously precipitated carbonate minerals (Zhang et al. 2013b). Therefore, due to water-sediment interactions, the groundwater Γ concentration exhibited a sharp increase in the discharge area, which was dominated by iodide. Due to strong evaporation, the Γ concentration in shallow groundwater can reach up to 2,180 µg/L, with a TDS value of 6,275 mg/L. The mixing of surface water and groundwater caused by recharge processes, such as irrigation, can also affect Γ concentrations. The distributions of truly dissolved and/or colloidal iodine, Fe and DOC are largely controlled by the redox potential and pH conditions of the groundwater system (Li et al. 2016a, b).

The Γ concentrations in the groundwater of the NCP ranged from 1.51 to 1,106 µg/L, with a median value of 51.28 µg/L; approximately 32.3% of groundwater Γ concentrations were higher than 150 µg/L. High- Γ groundwater is mainly distributed in the southern part of the Bohai Bay area,

thus reflecting the potential effects of the Bohai Sea (Li et al. 2017a). Vertically, although high- Γ groundwater occurs in all four aquifers, groundwater from deeper aquifers (>350 m) generally had higher Γ concentrations (Li et al. 2017a). In the NCP, along the groundwater flow path from Taihang Mountain to the Bohai seawater, groundwater Γ concentrations increased from 2.4 to 390.1 $\mu\text{g/L}$. The Bohai seawater had an Γ concentration of 51.1 $\mu\text{g/L}$. It can be postulated that during several events of seawater transgression, seawater Γ was potentially loaded onto sediment in coastal areas, given the strong assimilation of Γ onto organic matter and metal oxides/hydroxides (Dai et al. 2009; Shetaya et al. 2012; Shimamoto et al. 2011). Under favorable conditions, sediment Γ can be released into groundwater to form Γ -rich Na-Cl-type water in coastal areas (Li et al. 2017a).

High-salinity groundwater

In China, brackish and/or saline groundwater with high TDS (>1 g/L) values has been widely reported in nearly 20 provinces in northwestern (Chen et al. 2016; Ma 2016; Wang et al. 2016a; Wei et al. 2016a), northeastern (Han et al. 2015; Zhang et al. 2017), and northern China (Chen et al. 2014; Currell and Cartwright 2011; Han et al. 2014; Huang et al. 2015; Li et al. 2016a); eastern coastal areas such as the Laizhou Bay and the Pearl River Delta (Han et al. 2014; Huang et al. 2015; Wang and Jiao 2012; Xue et al. 2000); and central, southern and southwestern China (Lin et al. 2016; Wang et al. 2015b; Wang and Jiao 2012; Xu and Wang 2016)—for example, the groundwater in the Tarim Basin has a mean TDS value of 10.82 g/L, up to 350 g/L in some localities (Ma et al. 2010; Ruan et al. 2013; Zhao et al. 2016b). The TDS values in groundwater in the southern part of the Laizhou Bay can reach up to 184 g/L (Han et al. 2014; Xue et al. 2000). The total area with high-salinity groundwater has been gradually extending (Zhang et al. 2017).

High-salinity groundwater is usually associated with shallow aquifers. Deng et al. (2009) found that the TDS concentrations in the shallow aquifer of the Hetao Plain in Inner Mongolia can reach up to 7.46 g/L (Deng et al. 2009); Currell et al. (2010) found that most of the deep groundwater in the Yuncheng Basin has low TDS concentrations, with a median value of 1.09 g/L, while the shallow groundwater has TDS values of up to 8.45 g/L, with a median value of 2.01 g/L (Currell et al. 2010). Li et al. (2016a) also reported that 41% of the groundwater samples collected mostly from shallow aquifers in the Datong Basin are moderately saline, with TDS values of 3–10 g/L. Under the elevated vertical hydraulic gradients due to pumping, shallow high-salinity groundwater may leak into deeper aquifers, especially in places where preferential paths exist, as observed in the northern Sushui River Basin (Currell et al. 2010).

The processes responsible for the occurrence of high-salinity groundwater can be summarized as follows: firstly, evaporation and transpiration in arid and semiarid areas, as has been reported in inland basins such as the Dunhuang Basin and the Tarim River Basin in northwestern China (Huang and Pang 2012; Sun et al. 2016b). In these arid and semiarid regions, evaporation is the primary cause for high salinity in groundwater (Hao et al. 2000; Huang and Pang 2012). Transpiration is also important for increasing groundwater salinity, especially in oasis zones (Currell et al. 2010). Secondly, the modification and buildup of salinity through water–rock interactions is another factor contributing to the occurrence of high-salinity groundwater. Mineral dissolution significantly contributes to the buildup of salinity in the groundwater in the lower reaches of the Tarim River, in addition to evapotranspiration (Huang and Pang 2012). Similar mechanisms have also reported in the Ejina Basin (Wang et al. 2013a), the Jizhong Depression in the NCP (Chen et al. 2014), the Songnen Basin (Zhang et al. 2015a), the Datong Basin (Li et al. 2016a), and the Dunhuang Basin (Sun et al. 2016b). Thirdly, mixing with saline water also has a role in the occurrence of high-salinity groundwater. Groundwater salinity is reported to have been caused by seawater intrusion near coastal areas such as the Pearl River Delta (Wang and Jiao 2012), a coastal plain in southwestern Guangdong (Chen et al. 2016), the Huanghua Depression in the NCP (Chen et al. 2014), and the Laizhou Bay (Liu et al. 2016b). Regional water-table decline and extensive depression cones caused by intensive groundwater abstraction have disturbed the dynamic balance between freshwater and saline water, leading to the intrusion of saline water. The effects of human activities on groundwater salinity concentration include salt-flushing from agricultural irrigation (Wang et al. 2016a; Xie et al. 2013), the excessive use of chemical fertilizers (Zheng et al. 2017), and urban municipal and domestic wastewater discharge (Li et al. 2014e).

Elevation of groundwater salinity not only reduces available freshwater resources but has serious ecological consequences. The intrusion of high-salinity groundwater into freshwater aquifers has become an important environmental disaster (Han et al. 2011; Ma et al. 2007; Xue et al. 2000). High-salinity groundwater has been widely extracted for irrigation, extending the total area of secondary saline-alkaline land and aggravating slightly saline-alkaline land (Zhang et al. 2007; Zhang 2004; Chen et al. 2010). When the water table rises due to saline groundwater irrigation, capillary rise of saline groundwater causes the direct precipitation of evaporite minerals at the surface, leading to salinization when salts are concentrated in soils by the evaporation of freestanding irrigation water (Dehaan and Taylor 2002). Nearly 20% of irrigated land in China is threatened by salinization, and the proportion is still increasing (Li et al. 2014e). Irrigation with brackish water significantly raises the salinity of the soil (Ma

et al. 2010). The research of Ma et al. (2008) indicated that saline water irrigation causes the EC of the topsoil (0–100 cm) to be higher and more variable than the subsoil (100–180 cm) and the salt load rapidly increased, notably in the upper 80 cm in North China Plain.

Basic types of geogenic groundwater quality problems

As discussed in the preceding, geogenic groundwater problems are extremely complicated and affected by various coupled processes and factors. Based on the authors' 20 years of interdisciplinary research on the occurrence and hydrogeological conditions associated with geogenic groundwater quality problems inside and outside China, four basic types of their genesis and occurrence are summarized according to the main sources of the hazardous components and the predominant hydrogeochemical processes:

1. *Leaching-enrichment type*. The geogenic hazardous components with relatively high mobility can be leached from rocks/sediments in the recharge area of the regional groundwater system, and the groundwater can be further enriched by the time it reaches the discharge area of the groundwater system.
2. *Burial-dissolution type*. The aquifer matrix is the main source of geogenic hazardous components in groundwater. The sediments rich in hazardous components were accumulated as aquifer matrix via erosion, transport and deposition processes. Under favorable environmental conditions and the impact of hydrogeochemical processes (such as reductive dissolution process), the hazardous components can be dissolved and released from the aquifer matrix, especially from fine-grained sediments, into groundwater.
3. *Compaction-release type*. The source areas of the hazardous components are the hydrostatically deposited sediments (mostly lacustrine/swamp silts) of regional surface-water systems. Through surface runoff and weathering, the hazardous components can be accumulated in the sediments. During the processes of burial, compaction, consolidation and drainage of the sediments, the components can be released into the adjacent aquifers under favorable conditions.
4. *Evaporation-concentration type*. The source areas are the geogenic hazardous components in shallow groundwater systems, and due to the arid/semi-arid climate, shallow water table and strong evaporation, the hazardous components can be enriched in shallow groundwater.

These four basic types of genesis and occurrence of geogenic groundwater quality problems may jointly occur in the same region due to the variations of climate, sedimentary

environment and hydrogeological conditions, thereby leading to the co-occurrence of various geogenic hazardous components in groundwater. Due to the conservation of mass on the Earth, the continuous loss of materials in source areas will lead to a lack of specific components—for instance, due to the large amount of iodine leaching and loss from the Taihang Mountain areas in northern China, the iodine in groundwater there is commonly low, which has caused iodine deficiency disorders among local residents.

This theoretical framework of four basic types for the first time unifies the theories concerning the genesis of different types of worldwide geogenic groundwater quality problems, and has been supported by multidisciplinary evidence of hydrodynamics, hydrochemistry, isotope geochemistry and numerical simulation across the world.

Groundwater quality deterioration by anthropogenic activity

Groundwater quality deterioration due to domestic, agricultural, industrial and mining activities

Domestic, agricultural, industrial and mining activities have deteriorated the quality of groundwater; this has become a serious environmental and social problem for major cities undergoing rapid economic growth in China (Zheng and Liu 2013). According to the Ministry for Environmental Protection (MEP), the groundwater tested in 100 cities across China did not qualify as a source water for drinking. In 2011, the Ministry of Water Resources reported that 40% of rivers in China were classified as seriously polluted; of these, 20% were so polluted that their water quality was rated too toxic for human contact (Coulon et al. 2016; Hu et al. 2014). The main causes of groundwater quality deterioration include the excessive discharge of pollutants and the overexploitation of groundwater. As a result of both natural factors and human activities, it is estimated that 18% of groundwater in western China is of such poor quality that it cannot be directly used for multiple purposes (Li et al. 2016c). According to the Report on the State of the Environment in China, groundwater pollution in China is serious; only 40% of groundwater is suitable for drinking or fishing, and 28% is not suitable even for industrial purposes (Hu et al. 2014).

Industrial pollution is the main source of groundwater contamination (Wang 2007). A large amount of discharged industrial wastewater infiltrates groundwater due to intensive industrial activities and poor regulation, which causes groundwater to become loaded with different pollutants. Without sewage treatment plants, domestic sewage is discharged directly into surface water (rivers and canals) in many cities, and pollutants in surface water are transported into groundwater during groundwater recharge (Ma et al. 2012). Large linear

wastewater ponds that lack anti-seepage measures act as river channels that also cause the deterioration of groundwater quality in the semiarid area of the Lake Baiyangdian watershed in the NCP (Wang et al. 2014). The application of chemical fertilizer, animal manure and pesticides has increased food production; however, they can strongly affect groundwater quality via leaching, percolation, and soil erosion (Kaneko et al. 2005; Zhao and Li 2015), resulting in enrichment of contaminants such as $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, $\text{NO}_2\text{-N}$ and organic substances in subsurface. Nitrate contamination is a common problem in the groundwater of the NCP due to the overuse of fertilizers and the discharge of wastewater (Wang et al. 2016b). In addition, irrigation with polluted surface water also results in serious groundwater contamination—for example, the groundwater quality in Yanqi, which is a typical irrigation area in Xinjiang, has been deteriorating as a result of wastewater irrigation and the excessive application of fertilizers and pesticides (Di et al. 2015).

According to the Chinese Geochemical Investigation Report, the concentration levels of contaminants in 15% of investigated groundwater samples exceeded the national drinking water standard; the major contaminants are N-compounds, Fe, Mn, heavy metals and toxic trace organic contaminants (Wang et al. 2016c). The investigation of organic contaminants in groundwater in areas such as Beijing-Tianjing-Hebei, the YRD, the Pearl River Delta and the Huaihai Plain, found that trace amounts of toxic organic contaminants have generally been detected in cities and suburban areas (Lin and Wang 2017). N-compounds are major non-point contaminants that pose a great risk to Chinese groundwater quality, and they are mainly distributed in agricultural areas in northeastern and northern China and the Huaihe River Basin. The sources of N-compounds include fertilizer usage and livestock production, as well as landfill disposal and domestic sewage discharge. Along with the rapid economic development that China has been experiencing over the past 30 years, heavy metal pollution has become one of the major environmental issues in China. Pb, Cr, As, Cd, and Hg are the key heavy metal pollutants (Hu et al. 2014). The groundwater samples with Pb concentration exceeding the maximum concentration level (MCL, 0.01 mg/L for Pb) set by the National Drinking Water Standard (NDWS) were mainly distributed in the southern coastal area of Zhejiang Province, south of the NCP, and in the central and western areas of the Huai River Basin, while groundwater samples with excessive Cd contents are located in local areas of the NCP and the southeastern coastal area. The samples with Cr concentration exceeding MCL were mainly collected from areas near plants producing chromic salts, and several tens of Cr-contaminated sites were found. In comparison, samples with excessive Hg contents are much less common and are only distributed sporadically. In general, heavy metal contaminants were mainly detected in the areas near industrial plants and cities.

The toxic organic contaminants detected in groundwater mainly comprise monocyclic and polycyclic aromatic hydrocarbons, chlorinated solvents, antibiotics and pesticides. Most of these pollutants were found in groundwater samples collected from populated and economically developed areas such as the southeastern coast of China, and industrially developed cities such as Taiyuan, Shenyang, Tianjin, Jinan, and Wuhan. Industrial and domestic effluents from wastewater treatment plants and agricultural wastewater were major sources of organic contaminants in groundwater (Dong et al. 2017). Pesticides were mainly detected in groundwater samples from the Liaohe Plain, northern Xinjing, and Su-Xi-Chang regions (Lin and Wang 2017).

Oil, coal, and other minerals are abundant in western China. The development of these mineral resources has produced tremendous groundwater pollution (Li et al. 2017b). Coal mining activities have had a great impact on karst water quality in the Niangziguan spring catchment, which is one of the largest karst springs in northern China. Significant water quality deterioration was observed along the flow path, as was evidenced by the increasing sulfate, nitrate, and TDS contents of karst water (Wang et al. 2016c). Coal mine development has also caused groundwater contamination in northern Shanxi (Zhang et al. b). Petroleum contamination caused by the oil industry in the Longdong oilfield is the largest source of pollution that has led to the deterioration of water quality in the Malian River Basin of the Longdong Loess Plateau in northwestern China (Ma et al. 2012). The elevated concentrations of SO_4^{2-} and Cl^- in the groundwater in the piedmont region of Shijiazhuang could be mainly attributed to mining activities in the mountain area and discharge of municipal and industrial wastewater (Zhou et al. 2016).

Institutions and people involved in groundwater quality protection and management now face unprecedented challenges due to the effects of intense human activities and significant changes of the ecosystems. Groundwater quality monitoring networks are not well established in many regions, and those that exist have incomplete monitoring parameters and/or inadequate monitoring frequencies. Furthermore, manual monitoring is required in most regions of western China due to the high price of automated monitoring devices (Li et al. 2016c).

Changes in groundwater quality due to water diversion and surface water and groundwater interactions

In recent years, the contamination of surface water has been significant, especially in the Yellow River catchment, the Liaohe and Haihe River basins, and Taihu Lake catchment. Given that surface water and groundwater frequently interact with each other, the groundwater quality in China is greatly affected by water diversion and surface water and groundwater interactions (Hu 2014). The interaction and resulting

changes in groundwater quality have been explored in many areas such as the Jiangnan Plain (Duan 2016), the mid-lower reach of the Hanjiang River (Li et al. 2016f), the Jialu River Basin (Yang et al. 2012a) and the Songhua River Basin (Zhang et al. 2016a). The influence of polluted rivers on groundwater environments was qualitatively or semi-quantitatively investigated using soil columns or field experiments by some researchers (Chai and Lei 2004; Li et al. 2006). Duan (2016) found that changes in the redox environment and the input of surface-derived oxidants in aquifer systems are the main causes of seasonal changes in groundwater As concentrations in the Jiangnan Plain. Li et al. (2016f) estimated the dissolved solute flux from tributaries and groundwater to the river using a water-balance-budget model and an environmental-tracer mass balance approach. The transport processes of contaminants from surface water to groundwater have also been investigated in many areas (Hu 2014). Li et al. (2014c) indicated that surface water and groundwater interactions influenced the spatial distribution of trace metals and their transport in an alluvial fan of the Yellow River. A numerical simulation model was used to simulate and predict the transport and fate of contaminants under the effects of groundwater and surface-water interactions (Liang et al. 2003; Wang 2010; Yuan et al. 2011; Chen 2013; Yang 2011)—for example, Li (2003) simulated the infiltration, migration and transformation of pollutants in the Weihe River when groundwater was discharged to the river using in situ test data. The study found that pollutants can penetrate low-permeability strata and contaminate groundwater, although the low-permeability unsaturated zone hampered stream recharge. Song (2010) evaluated surface-water/groundwater interactions caused by phosphate mining activities using a numerical model. Li (2015) studied variations in groundwater quality affecting the main canal water quality in different situations using an established coupling numerical simulation model in the western mountains of Baoding.

To better manage and use water resources, water conservancy projects such as water diversion projects, dams and reservoirs have been widely implemented in China. The implementation of inter-basin water diversion projects increases the frequency and complexity of surface water and groundwater interactions. Furthermore, changes in surface water and groundwater interactions further affect groundwater quality (Du 2004; Huang and Pang 2010; Li et al. 2014b)—for example, Du (2004) studied the evolution of groundwater quality in southwestern Beijing after the implementation of the SNWT and analyzed changes in the chemical composition of the groundwater caused by the increase of the water level and the soaking of the unsaturated zone. Huang and Pang (2010) investigated changes in groundwater induced by water diversion in the lower Tarim River based on evidence provided by environmental isotopes and water chemistry. Irrigation using diverted water from the lower reaches of the Yellow

River in China has lasted for more than 50 years, and their effects on surface water and groundwater have been assessed (Liu et al. 2014; Kong et al. 2016). For example, the effect of irrigation practices on the transfer and regional migration mechanisms of nitrate (NO_3^-) in surface water and groundwater was investigated in an alluvial fan of the Yellow River (Li et al. 2014b), indicating that surface water and groundwater interactions influenced the spatial distribution of NO_3^- in the piedmont of the southern Taihang Mountains. Furthermore, the impact of ecological water diversion on the hydrogeochemical characterization of surface water and groundwater was evaluated in the Yellow River Delta using hydrochemical and isotopic methods (Liu et al. 2014). Jia et al. (2015) developed a linked surface water and groundwater simulation model to assess the impact of a trans-basin water diversion project on groundwater safety. Chen et al. (2015) studied seasonal variations in water quality in a lateral hyporheic zone in response to dam operations and determined that dam release-storage cycles were the dominant factor causing changes in lateral hyporheic flow and water quality.

Changes in groundwater quality affected by seawater/saline water intrusion

The intense groundwater exploitation in coastal areas has led to a continuous decrease in groundwater level. This situation, imposed by sea level rise, has triggered seawater intrusion, further increasing groundwater salinity and deteriorated groundwater quality. Seawater intrusion in China mainly occurs in the Circum-Bohai-Sea region such as Liaoning, Hebei, and Shandong provinces (Lin and Wang 2017)—for example, seawater intrusion affected an area of 3,076 km² in the Dongyin, Weifang, Qingdao, Weihai, and Rezhao areas in Shandong Province. An area of 740 km² in Jinzhou, Huludao, and Dalian in Liaoning Province was also affected by seawater intrusion, whereby the encroachment distance reached up to 5–8 km in Huludao, where the groundwater was intensively pumped (Lin and Wang 2017).

Since seawater intrusion in coastal aquifers induced by over-exploitation of groundwater has affected the quantity and quality of fresh groundwater resources (Zhang et al. 2015c), it has thus been regarded as a crucial geo-environmental problem in coastal regions such as Liaoning, Shandong and Jiangsu provinces (Wang 2007; Zhao et al. 2016a). The city of Dalian was one of the first cities in China that was found to have experienced seawater intrusion (Zhao et al. 2016a). Due to the uncontrolled groundwater abstraction that occurred from the 1980s to the 1990s in Dalian, the groundwater level continued to decrease and its depression cones became enlarged. Then, seawater intrusion, which increased the chloride concentrations in groundwater, resulted in the deterioration of groundwater quality. Similarly, the deep groundwater from the southern coastal region of

Tangshan has been severely affected by salinization, and the quality of the shallow groundwater in the north has also been affected by seawater intrusion (Ma et al. 2015). The shallow groundwater at Yuncheng Basin showed a clear increase in salinity along its regional flow paths toward the center of the basin, where a low-elevation inland salt lake is located (Li et al. 2016f). Saline water commonly exists in the shallower aquifer and freshwater commonly exists in the deeper aquifer in Hengshui District, which is located in the center of the NCP. Overexploitation in this region has caused the downward mitigation of shallow brine, leading to the salinization of deeper groundwater (Li et al. 2016e).

Anthropogenic eco-geological problems

The regional decline in groundwater level has also impacted groundwater-dependent ecosystems, thus causing wetlands to shrink or disappear and the degradation of vegetation coverage. Due to groundwater overdraft, land subsidence has occurred in more than 40 cities, among which Shanghai, Tianjin and Taiyuan experienced the maximum accumulative land subsidence (over 2 m). In addition, aquifer salinization has been caused by intensive irrigation in the NCP (Foster et al. 2004) and desertification has increased.

Ecosystem degradation

The continuous degradation of vegetation systems in arid areas over the past 50 years has not only constrained social and economic development but also affected ecological safety, thus threatening the environment in central and northwestern China (Cheng and Wang 2006). The degradation of vegetation systems in arid areas is closely associated with the unreasonable exploitation of groundwater resources.

The decreased water table caused by groundwater exploitation could affect the structure, distribution and dynamics of vegetation in groundwater-dependent ecosystems (Jolly et al. 2010). In China, most studies have focused on groundwater-dependent vegetation ecosystems that are mainly located in arid-semiarid inland areas in northwestern China (Zhao et al. 2005). There, the vegetation ecosystem has experienced severe degradation due to the water-table decline, which has been widely reported in the Tarim Basin, Yanqi Basin, Jungar Basin, Heihe River Basin (Fan et al. 2008), Yinchuan Plain (Jin et al. 2009) and Erjina Basin (Zhong et al. 2002). In inland arid basins, river water was intercepted by water conservancy projects upstream, leading to the drying of terminal lakes and acceleration of the aridity of the lower reaches of rivers—for example, the groundwater levels in the lower reaches of the Manasi River dropped by 5–8 m along the rivers, causing death of the vegetation along rivers and lakes (Lin and Wang 2017). The relationship between groundwater

and vegetation has been observed on both regional and local scales. On a regional scale, remote sensing using normalized difference vegetation index (NDVI) data was employed to establish the statistical relationship between the spatial distribution of vegetation cover and groundwater level and to assess the zonation of groundwater-dependent vegetation (Jin et al. 2007). On a local site scale, field experiments and monitoring at points and cross-sections were used to investigate the relationship between the ecological indicators of vegetation and the hydraulic factors of saturated and unsaturated water, as well as to reveal the water consumption patterns of vegetation (Sun et al. 2016a). Groundwater quality also exerts a control on vegetation growth. A previous study showed that most vegetation withered when the TDS content in the arid Tarim Basin was >10 g/L (Lin and Wang 2017). Some researchers argued that the water-table depth is a key factor determining vegetation growth and that the structure and function of a vegetation ecosystem will be maintained when the water table is maintained at a reasonable depth (Chen and Kang 1992; Guo and Liu 2005; Wang et al. 2001; Zhang et al. 2003). Thus, they proposed the concept of the ‘suitable water-table depth’, which is the optimal water-table depth for maintaining a vegetation ecosystem.

Soil salinization can occur both in coastal areas due to seawater intrusion and in arid-semiarid inland areas due rise of the water table (Chen and Kang 1992; Yuan 1964) when the soil type is clay or silty clay in an arid-semiarid climate. Soil salinization was also observed in both northwestern and eastern China and was reported to be associated with water-table depth, TDS, chemical components and flow conditions (Song and Deng 2000). Soil salinization could further alter the properties of soil and affect the productivity of crops. The critical water-table depth was used to control soil salinization when using groundwater resources.

Coastal ecosystems that depend on groundwater discharge have been affected by seawater intrusion. Seawater intrusion changes the salinity and chemical components of freshwater from coastal areas and can thus affect the ecosystems in these areas. The problems associated with this process include damage to the plant community caused by the deterioration of soil properties and a decrease in the soil organic matter content, as well as changes in the structure of fish ecosystems due to changes in the salinity, chemical components, and concentrations of nutrient elements in aquatic environments (Han 2013; Tang 1995; Tang and Zhang 2011). For example, the regressive succession and degradation of the plant community in Layzhou Bay, Yantai, were reported to have been caused by seawater intrusion which, in turn, promoted further seawater intrusion (Tang and Zhang 2011).

River or lake base flow can maintain habitats for aquatic life, the equilibrium of the river ecosystem and the self-cleaning capacity of the water body. Efforts were made to calculate the ecological river or lake base flow flux based on

the demands of aquatic life in the water habitat (Li et al. 2006). Many studies have reported that the base flow in rivers and lakes has been greatly reduced due to the overexploitation of groundwater in China. Consequently, aquatic ecosystems have been degraded. The decreased base flow in rivers and lakes and the associated degradation of riparian ecosystems has been widely reported in areas such as Xinjing (Jia and Ci 2000; Jia and Xu 1998), the coastal area of Bohai and the Yellow Sea (Yang 2006). For example, the groundwater level in an alluvial fan of the Geermu catchment decreased by 0.85 m due to the construction of a reservoir and groundwater exploitation in its upper reaches in comparison with its natural condition, leading to a decrease in the river base flow and changes in the eco-environment (Wang et al. 2001). Wetlands were also seriously degraded—for example, the wetland area in the Songnen Plain decreased by $65.80 \times 10^4 \text{ km}^2$ at a rate of $4.39 \times 10^4 \text{ km}^2/\text{year}$ over the past 20 years. Two-thirds of the 4,000 swamps in the Sanjiang Plain have disappeared due to groundwater level decrease.

Land subsidence

Land subsidence and its induced ground fissures have been caused by excessive groundwater withdrawal in more than 50 cities in China (Zhang et al. 2008; Zhu et al. b). These cities are mainly distributed in coastal regions and river deltas such as the YRD, as well as sedimentary plains comprising porous media such as the NCP and the Fenwei Graben (Hu et al. 2004). The total area that has been affected by subsidence in China was approximately $4.9 \times 10^4 \text{ km}^2$ in the 1990s (Duan 1998), which increased to $7.9 \times 10^4 \text{ km}^2$ in the 2000s (Xue et al. 2005; Yi et al. 2011) and further increased to more than $9 \times 10^4 \text{ km}^2$ in 2012 (Wang 2016). The maximum accumulated subsidence can reach up to more than 2–3 m in some areas such as Tianjin in NCP (Yi et al. 2011), Shanghai in the YRD (Shi et al. 2008) and Taiyuan in the Fenwei Graben (Ma et al. 2005). Changes in the rate of land subsidence correspond to the degree of groundwater withdrawal. Most of the regions that have subsided experienced their maximum subsidence rates during the 1970s to 1980s. In response to the recent decline in groundwater exploitation and the artificial recharge of groundwater, the subsidence rate has slowed down in some regions such as Shanghai. However, the areas that have been affected by subsidence are still extending, and more than 11 cities have experienced accumulative subsidence of greater than 1 m at their subsidence centers, including Shanghai, Suzhou, Wuxi, Changzhou, Tianjin, Cangzhou, An'yang, Fuyang, Xi'an, Taiyuan and Taibei (Hu et al. 2004).

The land subsidence in these regions has mainly been caused by excessive groundwater abstraction, which is evidenced by the close correlation between the spatiotemporal development of subsidence and the distribution of withdrawal in different areas of subsidence (Ma et al. 2006; Shi et al. 2007;

Zhu et al. b). Although tectonic movement could also be responsible for land subsidence, its effect is negligible compared to the influence of groundwater exploitation (Ma et al. 2006; Yan et al. 2006). The heterogeneity of the aquifer (e.g., the distribution of clay or muddy clay layers) can also have an impact on the distribution of land subsidence (Ma et al. 2006; Sun et al. 2007).

The occurrence of land subsidence areas in China not only caused the sinking and destruction of constructed infrastructures such as buildings, highways, subways and tunnels (Hu et al. 2004), but also induced floods and seawater intrusion (Wang et al. 2012), the reduction of groundwater storage (Chen et al. 2003) and the degradation of groundwater quality (Liu et al. 2001). The compaction of aquitards reduced the hydraulic conductivity of the third mud layer (aquitard) in Suzhou, Jiangsu Province, by over 30% from 1983 to 1997 (Lin and Wang 2017). The consolidation of sediments decreased the ground elevation. As a result, the drainage capability decreased, which led to inland floods and coastal storm surges, which are common in the YRD and NCP. For example, four storm surges occurred in Tianjin in the NCP in 1985, 1992, 1997 and 2003, destroying multiple tidal embankments and causing a series of ecological and social problems (Hu et al. 2008). In Shanghai, rainfall flooding occurred 22 times at a rate of almost twice per year from 1981 to 1994 (Chai et al. 2004). The decrease in ground surface elevation also reduced the groundwater depth, resulting in farmland submergence and soil salinization.

Monitoring data are critical for both land subsidence modeling and its control. Regional land subsidence networks have been established in the YRD and the NCP, which monitor factors including the dynamic groundwater level and land subsidence (Lin and Wang 2017).

Desertification in both northwest and southwest arid areas

Desertification in China mainly includes sandy desertification and rocky desertification, which are mainly distributed in the northwestern and southwestern areas of China, respectively. Desertification degrades the ecological environment and becomes the primary factor that prevents sustainable development and social stability in many regions around the world (Li et al. 2016d; Mainguet 1991; Reynolds and Smith 2002; Williams and Balling Jr 2005).

Approximately 95.64% of the sandy desertification area is distributed in five provinces in northern and northwestern China, including Xinjiang, Inner Mongolia, Tibet, Gansu and Qinghai provinces as shown in Fig. 5 (Li et al. 2015). The total land area affected by desert and desertification comprises $288.5 \times 10^4 \text{ km}^2$, which accounts for 30% of the area of China (Lin and Wang 2017), whereby the desertification area occupies 73.5% of the area of Inner Mongolia, 47.7% of Xinjiang, 54.7% of Gansu, and 46% of Qinhai (Ge et al.

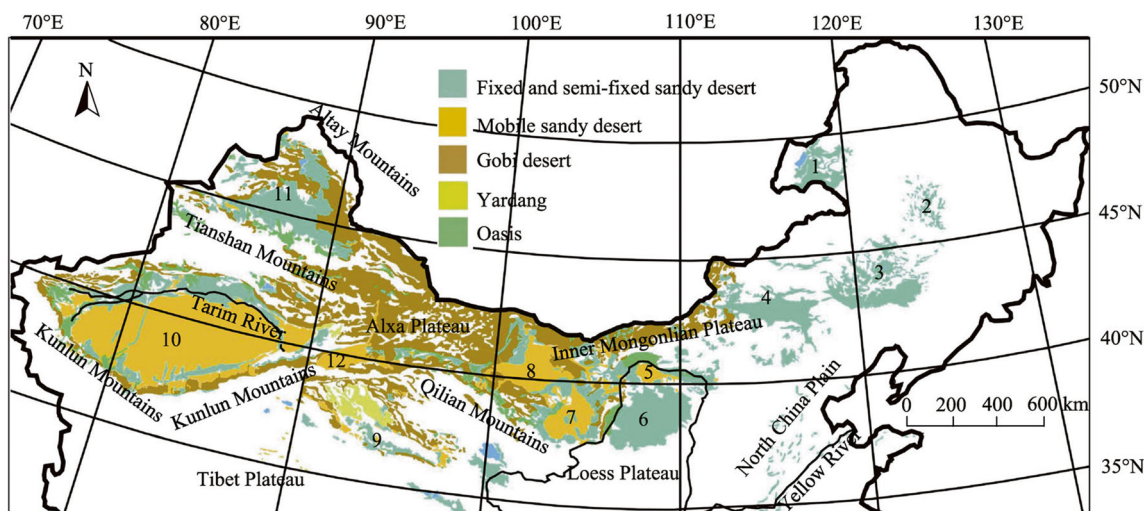


Fig. 5 Distribution of sandy land and deserts in northern China (Li et al. 2015b). (The numbers show the locations and type of desertification. 1 Hulun Buir sandy land; 2 Nenjiang sandy land; 3 Horqin sandy land; 4

Hunshandake sandy land; 5 Hobq desert; 6 Mu Us sandy land; 7 Tengger Desert; 8 Badain Jaran Desert; 9 Qaidam Desert; 10 Taklimakan Desert; 11 Gurbantunggut Desert; 12 Kumtag Desert)

2016; Li et al. 2015; Lin and Wang 2017; Liu et al. 2016a; Wang et al. 2013b; Yan et al. 2015; Yang et al. 2005; Zhang et al. 2015b).

The term “rocky desertification” is used to characterize the processes that transform a karst area covered by vegetation and soil into a rocky landscape that is almost devoid of soil and vegetation (Yuan 1997). Rocky desertification primarily occurs in southwestern China due to the effects of extensive human activities on ecologically fragile carbonate rocky formations. China contains a rocky desertification area of approximately 0.12 million km² in the southwestern karst area, which is distributed in seven provinces (Yunnan, Guizhou, Guangdong, Chongqing, Hunan, Hubei, Sichuan) and Guangxi autonomous region (Jiang et al. 2014) (Fig. 6). Rocky desertification is the primary ecological disaster that has significantly hindered economic growth in southwestern China and has had a direct impact on the millions of people living there (Jiang and Yuan 2003)—for example, the rocky desertification area in Guangxi, which is renowned for its representative tropical karst landforms, is approximately 28,400 km² (Jiang et al. 2014).

In addition to climate conditions and human activities, water is the major factor affecting desertification processes, as water conditions determine the total vegetation cover area to a large extent, especially in arid-semiarid areas (Yan et al. 2015). Many studies have concluded that the overexploitation and overutilization of groundwater resources in the artificial oases in the middle reaches could cause the degradation of the ecological environment, leading to the desertification of the natural oases in downstream reaches (Kang et al. 2004; Fang and Sun 2006; Dong 2009; Xie 2004; Du et al. 1996). Groundwater is one of most important water resources supplied to plants, and has strong interactions with surface water and the atmosphere in arid and semiarid regions; therefore, the

water-table depth is the primary factor controlling desertification if the amount of intervention from human activity is negligible (Su et al. 2005). Thus, it was suggested that the most fundamental approach to controlling desertification be the rational exploitation of water resources and the maintenance of optimal groundwater levels (Tursun et al. 2008).

Summary and perspective

To maintain its economic development, China has had to extract groundwater as a major source of water supply; however, the groundwater level has been greatly reduced due to the overexploitation of groundwater reserves over the past several decades. The groundwater quality has also deteriorated due to the effects of both intense human activities and geogenic processes. Consequently, a series of ecological and geo-environmental problems have been induced by changes in the quantity and quality of groundwater; thus, the effects of rapid economic growth on groundwater systems should be monitored, understood and predicted for safe and sustainable groundwater supply. The current monitoring networks in mainland China were established and maintained by the Ministry of Water Resources, Ministry of Land and Resources and Ministry of Environmental Protection, with focus on the monitoring of groundwater quantity, geo-environment induced by over-extraction of groundwater, and groundwater contamination, respectively. A total of 24,515 groundwater level monitoring stations were established by the Ministry of Water Resources by 2013 (Ma 2012; Jin et al. 2013), and a total of 4,778 groundwater quality stations were built in 203 cities by 2016 (Wei et al. 2016b). The groundwater environment monitoring system has not been completed and most monitoring wells are located within wellhead areas (Wei et al. 2016b).

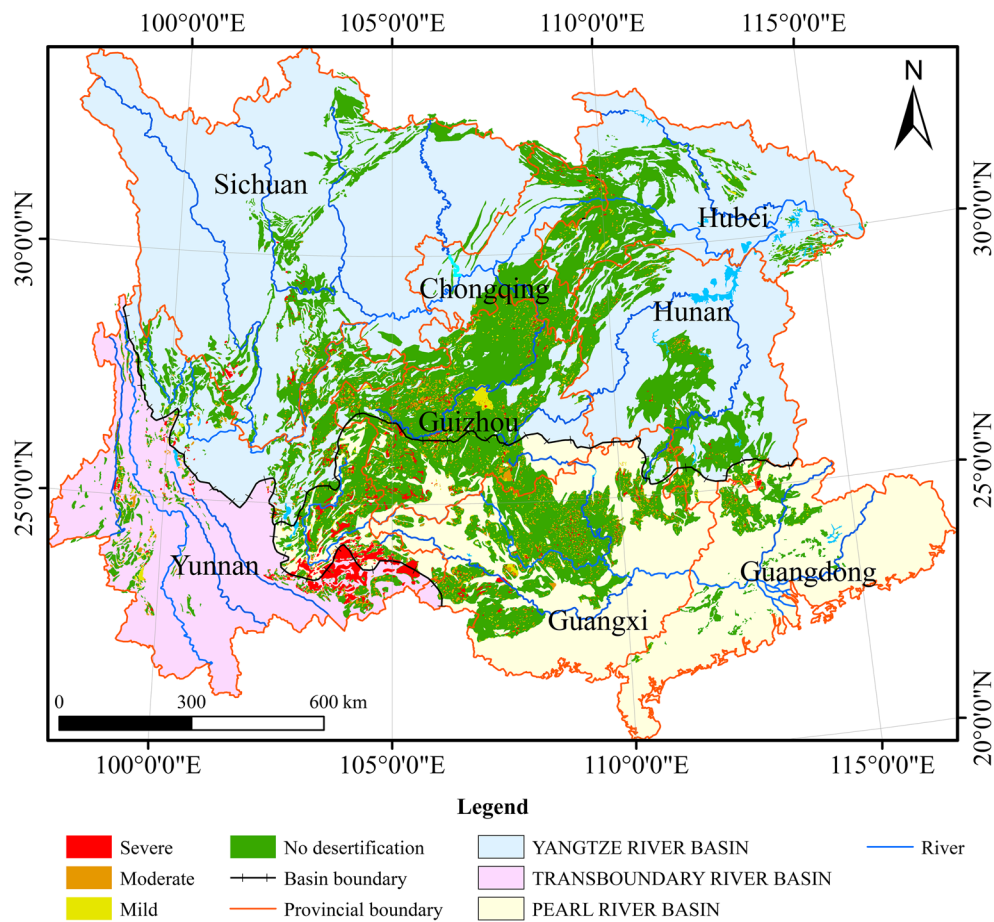


Fig. 6 Distribution and classification of rocky desertification areas in southwest China (Jiang 2014)

The impact of large-scale water conservancy projects on groundwater systems should be investigated to achieve sustainable water resource management. To better monitor, predict and manage groundwater flow, certain research aspects are of priority in order to establish the evolution of groundwater systems under rapid economic development.

1. The monitoring and simulation of the evolution of the groundwater system and its effects on the ecological system and geo-environment are fundamental for groundwater management. High-precision, high-resolution, and high-frequency depth-specific monitoring and field experiments are very useful for observing the behavior of groundwater flow and contaminant transport, which are required to improve the current monitoring system in China. Multiple methods, including geophysical, geochemical and isotopic tracing methods, should be integrated with hydrogeological methods to observe, model and predict the changes in properties and behavior of groundwater systems. In addition to traditional monitoring methods, interpretation of remote sensing and satellites data proves to be very useful for monitoring large-scale changes in groundwater systems and should be included in Chinese regional groundwater monitoring systems.
2. Coupled groundwater and surface-water models, which can simulate changes in both water quality and quantity caused by different impacts, should be used in large basins and catchments to simulate and predict the evolution of groundwater systems. These models can also consider the effects of water conservancy projects on groundwater systems. Optimization models should be further employed to optimize groundwater use among different areas and the demands from different users without constraints reflecting the occurrence of different ecological and geological environmental problems.
3. More cost-effective and user-friendly remediation technologies to clean up contaminated aquifers need to be invented, tested and applied, which is especially important for distant and poor regions where there are no alternative sources for water supply. Geo-environmental engineering that aims to cost-effectively in situ remove or fix geogenic and/or anthropogenic contaminants in contaminated aquifers will become an increasing important cross-discipline, linking hydrogeology and environmental engineering.
4. Studies of groundwater flow systems, groundwater-dependent ecosystems, and eco-environmental problems associated with changes in groundwater systems involve multiple disciplines such as hydrogeology, ecology,

economy, management, law, and climate change. Thus, hydrogeological studies should be incorporated with these disciplines to resolve groundwater-associated problems and better manage groundwater resources.

Acknowledgements This research was financially supported by the Grant for Innovative Research Groups of the National Natural Science Foundation of China (NSFC) (Grant No.41521001). We thank Prof. Xueyu Lin of Jilin University for her invaluable advice and continuous support. Under her leadership, we implemented the research project on Hydrogeology Discipline Development Strategies supported by NSFC and Chinese Academy of Science (Grant No. L1724016), together with our colleagues across China. As a matter of fact, this special issue is dedicated to her and her contemporaries of the Chinese community of hydrogeologists, to express our sincerely gratitude to them as our teachers for their great contributions to the development of hydrogeology in China.

References

- Aeschbachhertig W, Gleeson T (2012) Regional strategies for the accelerating global problem of groundwater depletion. *Nat Geosci* 5:853–861
- Aishan T, Halik Ü, Cyffka B, Kuba M, Abliz A, Baidourela A (2013) Monitoring the hydrological and ecological response to water diversion in the lower reaches of the Tarim River, Northwest China. *Quat Int* 311:155–162
- Alam SMM, Farha MN, Zaman AKB (2015) An appraisal of arsenic and pesticide toxicity for economically terminal people: a snap shot of north-western part of Bangladesh. *J Sci Res* 7:159
- Ali S, Thakur SK, Sarkar A, Shekhar S (2016) Worldwide contamination of water by fluoride. *Environ Chem Lett* 14(3):291–315
- Ayoub S, Gupta AK (2006) Fluoride in drinking water: a review on the status and stress effects. *Crit Rev Environ Sci Technol* 36:433–487
- Brunner P, Li HT, Kinzelbach W, Li WP, Dong XG (2008) Extracting phreatic evaporation from remotely sensed maps of evapotranspiration. *Water Resour Res* 44(8):1291–1295. <https://doi.org/10.1029/2007WR006063>
- Cai X, Ringler C (2007) Balancing agricultural and environmental water needs in China: alternative scenarios and policy options. *Water Policy* 9:95–108
- Cao G, Zheng C, Scanlon BR, Liu J, Li W (2015) Use of flow modeling to assess sustainability of groundwater resources in the North China plain. *Water Resour Res* 49:159–175
- Chai HW, Lei MQ (2004) The simulated analysis of contamination evolution of underground water by Jinti River. *Soil Eng Found* 18:61–63
- Chai JC, Shen SL, Zhu HH, Zhang XL (2004) Land subsidence due to groundwater drawdown in Shanghai. *Géotechnique* 54:143–147
- Chen L (2013) Modeling of the water flow and nitrate transport in the shallow aquifer of the Shaying River Basin and its contribution to river pollution (in Chinese with English abstract). MSc Thesis, Nanjing University, Nanjing, China
- Chen H, Kang Y (1992) Condensed vapor and its role in the ecological environment of Shapotou region (in Chinese with English abstract). *J Arid Res Environ* 6:63–72
- Chen C, Pei S, Jiao J (2003) Land subsidence caused by groundwater exploitation in Suzhou City, China. *Hydrogeol J* 11:275–287
- Chen W, Hou Z, Wu L, Liang Y, Wei C (2010) Evaluating salinity distribution in soil irrigated with saline water in arid regions of Northwest China. *Agric Water Manag* 97(12):2001–2008
- Chen L, Ma T, Du Y, Yang J, Liu L, Shan H, Liu C, Cai H (2014) Origin and evolution of formation water in North China plain based on hydrochemistry and stable isotopes (^2H , ^{18}O , ^{37}Cl and ^{81}Br). *J Geochem Explor* 145:250–259
- Chen X, Chen L, Zhao J (2015) Seasonal variation of water quality in a lateral hyporheic zone with response to dam operations. AGU Fall Meeting, San Francisco, December 2015
- Chen L, Ma T, Du Y, Xiao C, Chen X, Liu C, Wang Y (2016) Hydrochemical and isotopic (^2H , ^{18}O and ^{37}Cl) constraints on evolution of geothermal water in coastal plain of southwestern Guangdong Province, China. *J Volcanol Geother Res* 318:45–54
- Cheng G, Jin H (2012) Permafrost and groundwater on the Qinghai-Tibet plateau and in Northeast China. *Hydrogeol J* 21:5–23
- Cheng GD, Wang GX (2006) Changing trend of drought and drought disaster in Northwest China and countermeasures (in Chinese with English abstract). *Earth Sci Front* 13:3–14
- Cheng G, Xin L, Zhao W, Xu Z, Qi F, Xiao S, Xiao H (2014) Integrated study of the water-ecosystem-economy in the Heihe River basin. *NSR* 1(3):413–428
- Coulon F, Jones K, Li H, Hu Q, Gao J, Li F, Chen M, Zhu YG, Liu R, Liu M (2016) China's soil and groundwater management challenges: lessons from the UK's experience and opportunities for China. *Environ Int* 91:196–200
- Currell MJ, Cartwright I (2011) Major-ion chemistry, $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ as indicators of hydrochemical evolution and sources of salinity in groundwater in the Yuncheng Basin, China. *Hydrogeol J* 19:835–850
- Currell MJ, Cartwright I, Bradley DC, Han D (2010) Recharge history and controls on groundwater quality in the Yuncheng Basin, North China. *J Hydrol* 385:216–229
- Currell M, Cartwright I, Raveggi M, Han D (2011) Controls on elevated fluoride and arsenic concentrations in groundwater from the Yuncheng Basin, China. *Appl Geochem* 26:540–552
- Dai JL, Zhang M, Hu QH, Huang YZ, Wang RQ, Zhu YG (2009) Adsorption and desorption of iodine by various Chinese soils: II. iodide and iodate. *Geoderma* 153:130–135
- Dehaan RL, Taylor GR (2002) Field-derived spectra of salinized soils and vegetation as indicators of irrigation-induced soil salinization. *Remote Sens Environ* 80(3):406–417
- Deng YM, Wang YX, Ma T (2009) Isotope and minor element geochemistry of high arsenic groundwater from Hangjinhouqi, the Hetao plain, Inner Mongolia. *Appl Geochem* 24:587–599
- Di FY, Dong XG, Yang PN (2015) Analysis on situation of groundwater quality and change trends in Yanqi County typical irrigation area of Xinjiang, Yellow River (in Chinese with English abstract). 37:76–78
- Döll P, Hoffmann-Dobrev H, Portmann FT, Siebert S, Eicker A, Rodell M, Strassberg G, Scanlon BR (2012) Impact of water withdrawals from groundwater and surface water on continental water storage variations. *J Geodyn* 59–60:143–156
- Dong PH (2009) Evaluation on the water-land resource of space layout and constitution in Gansu Province (in Chinese with English abstract). *Arid Land Geogr* 32(6):834–840
- Dong W, Xie W, Su X, Wen C, Cao Z, Wan Y (2018) Review: Micro-organic contaminants in groundwater in China. *Hydrogeol J* <https://doi.org/10.1007/s10040-018-1760-z>
- Du T (2004) A study of test simulation on groundwater quality evolution after the South-to-North Water Transfer in southwestern area, Beijing (in Chinese with English abstract). MSc Thesis, Jilin University, Jinlin, China
- Du H, Gao Q, Li F (1996) Trend analysis of surface water resources and dynamics in the interior drainage basins of Hexi Area (in Chinese with English abstract). *J Nat Resour* 2:44–54
- Duan Y (1998) Research status on land subsidence and sustainable development in the 21st century of China (in Chinese with English abstract). *Chin J Geol Hazard Control* 9(2):1–5
- Duan YH (2016) Seasonal variations of groundwater arsenic concentration in shallow aquifers at Jiangnan Plain (in Chinese with English abstract). PhD Thesis, China University of Geosciences, Beijing

- Fan ZL, Chen YN, Ma YJ, Li HP, Alishir K, Abdimijit (2008) Determination of suitable ecological groundwater depth in arid areas in northwest part of China (in Chinese with English abstract). *J Arid Land Resour Environ* 22(2):1–5
- Fang C, Sun X (2006) Mechanism of urban system development and its space organization in northwest arid area with scarcity of water resource: the case of Hexi corridor (in Chinese with English abstract). *J Desert Res* 26:860–867
- Feng W, Zhong M, Lemoine JM, Biancale R, Hsu HT, Xia J (2013) Evaluation of groundwater depletion in North China using the gravity recovery and climate experiment (GRACE) data and ground-based measurements. *Water Resour Res* 49(4):2110–2118
- Foster S, Garduno H, Evans R, Olson D, Tian Y, Zhang W, Han Z (2004) Quaternary aquifer of the North China plain: assessing and achieving groundwater resource sustainability. *Hydrogeol J* 12:81–93
- Gao X, Wang Y, Li Y, Guo Q (2007) Enrichment of fluoride in groundwater under the impact of saline water intrusion at the salt lake area of Yuncheng basin, northern China. *Environ Geol* 53:795–803
- Gates JB, Scanlon BR, Mu X, Zhang L (2011) Impacts of soil conservation on groundwater recharge in the semi-arid loess plateau, China. *Hydrogeol J* 19:865–875
- Ge X, Dong K, Luloff AE, Wang L, Xiao J (2016) Impact of land use intensity on sandy desertification: an evidence from Horqin Sandy Land, China. *Ecol Indicators* 61:346–358
- Gorelick SM, Zheng C (2015) Global change and the groundwater management challenge. *Water Resour Res* 51:3031–3051
- Guo Q (2012) Hydrogeochemistry of high-temperature geothermal systems in China: a review. *Appl Geochem* 27:1887–1898
- Guo Z, Liu H (2005) Eco-depth of groundwater table for natural vegetation in inland basin, northwestern China. *J Arid Land Res Environ* 19:157–161
- Guo Q, Wang Y (2012) Geochemistry of hot springs in the Tengchong hydrothermal areas, southwestern China. *J Volcanol Geother Res* 215–216:61–73
- Guo H, Tang X, Yang S, Shen Z (2008) Effect of indigenous bacteria on geochemical behavior of arsenic in aquifer sediments from the Hetao Basin, Inner Mongolia: evidence from sediment incubations. *Appl Geochem* 23:3267–3277
- Guo Q, Wang Y, Liu W (2009) Hydrogeochemistry and environmental impact of geothermal waters from Yangyi of Tibet, China. *J Volcanol Geother Res* 180:9–20
- Guo H, Wen D, Liu Z, Jia Y, Guo Q (2014a) A review of high arsenic groundwater in Mainland and Taiwan, China: Distribution, characteristics and geochemical processes. *Appl Geochem* 41: 196–217.
- Guo Q, Liu M, Li J, Zhang X, Wang Y (2014b) Acid hot springs discharged from the Rehai hydrothermal system of the Tengchong volcanic area (China): formed via magmatic fluid absorption or geothermal steam heating? *Bull Volcanol* 76:868
- Guo F, Jiang G, Polk JS, Huang X, Huang S (2015) Resilience of groundwater impacted by land use and climate change in a karst aquifer, South China. *Water Environ Res* 87:1990–1998
- Guo Q, Liu M, Li J, Zhang X, Guo W, Wang Y (2017) Fluid geochemical constraints on the heat source and reservoir temperature of the Banglazhang hydrothermal system, Yunnan-Tibet Geothermal Province, China. *J Geochem Explor* 172:109–119
- Han G (2013) Comprehensive evaluation of seawater intrusion and ecological rehabilitation technology (in Chinese). MSc Thesis, Yantai University, Shandong Sheng, China
- Han D, Kohfahl C, Song X, Xiao G, Yang J (2011) Geochemical and isotopic evidence for palaeo-seawater intrusion into the south coast aquifer of Laizhou Bay China. *Appl Geochem* 26:863–883
- Han DM, Song XF, Currell MJ, Yang JL, Xiao GQ (2014) Chemical and isotopic constraints on evolution of groundwater salinization in the coastal plain aquifer of Laizhou Bay, China. *J Hydrol* 508:12–27
- Han D, Post VEA, Song X (2015) Groundwater salinization processes and reversibility of seawater intrusion in coastal carbonate aquifers. *J Hydrol* 531:1067–1080
- Hao AB, Li WP, Liang ZQ (2000) An approach to determine salinity contribution from mineral dissolution and evaporation for groundwaters in arid inland basin plain based on TDS and $\delta^{18}\text{O}$ (in Chinese with English abstract). *Hydrogeol Eng Geol* 1:4–6. <https://doi.org/10.16030/j.cnki.issn.1000-3665.2000.01.002>
- Hao Y, Yeh TCJ, Gao Z, Wang Y, Zhao Y (2006) A gray system model for studying the response to climatic change: the Liulin karst springs, China. *J Hydrol* 328:668–676
- He J, Charlet L (2013) A review of arsenic presence in China drinking water. *J Hydrol* 492:79–88
- He J, An YH, Han SB (2008) Distribution and sources of fluorine ion in groundwater in Ganzhou district of Zhangye City (in Chinese with English abstract). *Water Resour Protect* 24(6):53–56
- He J, Zhang FC, Han SB, Li XF, Yao XJ, Zhang H (2010) The distribution and genetic types of high-fluoride groundwater in northern China (in Chinese with English abstract). *Geol China* 37:621–626
- Hu HZ (2014) Study of reactive transport of reclaimed water through vadose zone and its impact on the groundwater environment with prevention measures of seepage in lakes and rivers (in Chinese with English abstract). PhD Thesis, China Agricultural University, Beijing
- Hu RL, Yue ZQ, Wang LC, Wang SJ (2004) Review on current status and challenging issues of land subsidence in China. *Eng Geol* 76:65–77
- Hu BB, Jiang YX, Zhou J, Wang J, Xu SY (2008) Assessment and zonation of land subsidence disaster risk of Tianjin Binhai Area (in Chinese with English abstract). *Sci Geogr Sin* 28(5):693–697
- Hu H, Jin Q, Kavan P (2014) A study of heavy metal pollution in China: current status, pollution-control policies and countermeasures. *Sustainability* 6:5820–5838
- Hua PL, Xi Q, Han GY, Liu JP, Zhang YM, Zhao YQ, Ma Y (2007) Investigation on iodine concentration in drinking water in Zhangjiakou City in 2003 (in Chinese with English abstract). *Chin J Endemil* 26:560–561
- Hua S, Liang J, Zeng G, Xu M, Zhang C, Yuan Y, Li X, Li P, Liu J, Huang L (2015) How to manage future groundwater resource of China under climate change and urbanization: an optimal stage investment design from modern portfolio theory. *Water Res* 85:31–37
- Huang TM, Pang ZH (2010) Changes in groundwater induced by water diversion in the lower Tarim River, Xinjiang Uygur, NW China: evidence from environmental isotopes and water chemistry. *J Hydrol* 387:188–201
- Huang T, Pang Z (2012) The role of deuterium excess in determining the water salinisation mechanism: a case study of the arid Tarim River basin, NW China. *Appl Geochem* 27:2382–2388
- Huang SB, Han ZT, Zhao L, Kong XK (2015) Hydrochemistry indicating groundwater contamination and the potential fate of chlorohydrocarbons in combined polluted groundwater: a case study at a contamination site in North China. *Bull Environ Cont Toxicol* 94:589–597
- Jadhav SV, Bringas E, Yadav GD, Rathod VK, Ortiz I, Marathe KV (2015) Arsenic and fluoride contaminated groundwaters: a review of current technologies for contaminants removal. *J Environ Manag* 162:306–325
- Jia B, Ci L (2000) The primary estimation of water demand by the eco-environment in Xinjiang (in Chinese with English abstract). *Acta Ecol Sin* 20:243–250
- Jia Y, Guo H (2013) Hot topics and trends in the study of high arsenic groundwater (in Chinese with English abstract). *Adv Earth Science* 28:51–61
- Jia B, Xu Y (1998) The conception of the eco-environmental water demand and its classification in arid land: taking Xinjiang as an example (in Chinese with English abstract). *Arid Land Geogr* 21(2):8–12
- Jia H, Liang S, Zhang Y (2015) Assessing the impact on groundwater safety of inter-basin water transfer using a coupled modeling approach. *Front Environ Sci Eng* 9:84–95

- Jiang ZC, Yuan DX (2003) Rocky desertification in southwest karst region and its comprehensive management. China Geological Survey Bureau Karst Groundwater and Desertification research papers of China Guangxi (in Chinese with English abstract). Science and Technology Press, Nanning, China, pp 13–19
- Jiang Z, Lian Y, Qin X (2014) Rocky desertification in Southwest China: impacts, causes, and restoration. *Earth Sci Rev* 132:1–12
- Jiao JJ, Wang XS, Nandy S (2006) Preliminary assessment of the impacts of deep foundations and land reclamation on groundwater flow in a coastal area in Hong Kong, China. *Hydrogeol J* 14:100–114
- Jiao X, Wang L, Wang L (2013) Evaluation of iodine concentration in drinking water at Puyang in 2011, China (in Chinese). *J Endemil* 32: 590–590
- Jin X, Wan L, Zhang Y, Xue Z, Yin Y (2007) A study of the relationship between vegetation growth and groundwater in the Yinchuan plain (in Chinese with English abstract). *Earth Sci Front* 14:197–203
- Jin X, Hu G, Shi X (2009) Relationship between soil salinization and the vegetation growing, groundwater depth in the Yinchuan plain (in Chinese with English abstract). *Geoscience* 23:23–27
- Jin LX, Liu WJ, Wang D, Zhu Q, Bai H, Sun YP (2013) The establishment and management of Chinese groundwater environment monitoring network (in Chinese with English abstract). *Environ Monit Forewarning* 5(2):1–4
- Jolly ID, Mcewan KL, Holland KL (2010) A review of groundwater-surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology. *Ecohydrology* 1:43–58
- Kaneko S, Kondoh A, Shen Y, Tang C (2005) The relation among the water cycle, grain production and human activities in the North China plain. *Suimon Mizu Shigen Gakkaishi (J Jpn Soc Hydrol Water Res)* 18:575–583
- Kang ES, Xin LI, Zhang JS, Hu XL (2004) Water resources relating to desertification in the Hexi area of Gansu Province, China. *J Glaciol Geocryol* 26:657–667
- Kendy E, Zhang Y, Liu C, Wang J, Steenhuis T (2004) Groundwater recharge from irrigated cropland in the North China plain: case study of Luancheng County, Hebei Province, 1949–2000. *Hydrol Process* 18:2289–2302
- Kinzelbach W, Bauer P, Siegfried T, Brunner P (2003) Sustainable groundwater management: problems and scientific tools. *Episodes* 26(4):279–284
- Kong XL, Wang SQ, Zhao H, Yuan RQ (2015) Distribution characteristics and source of fluoride in groundwater in lower plain area of North China plain: a case study in Nanpi County. *Environ Sci* 36: 4051–4059
- Kong X, Wang S, Liu B, Sun H (2016) Effect of water diversion on hydro-chemical characteristics of surface water and groundwater in lowland area of the North China plain: a case study of Nanpi County, Hebei Province (in Chinese with English abstract). *Chin J Eco-Agric* 24:1135–1144
- Konikow LF (2011) Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophys Res Lett* 38:245–255
- Li YT (2003) Study on the penetration mechanism and influence on groundwater by pollution of Weihe River using the field test and numerical model (in Chinese with English abstract). MSc Thesis, Chang'an University, Beilin, China
- Li WW (2015) Research on coupling simulation of surface and groundwater in inner row section of the middle South-to-North Water Diversion Project (in Chinese with English abstract). MSc Thesis, China University of Geosciences, Beijing
- Li P (2016) Groundwater quality in western China: challenges and paths forward for groundwater quality research in western China. *Expos Health* 8:305–310
- Li HM, Chen HH, Zheng XL (2006) Application of riverbed aquiferous system to indoor simulation of decontamination of aromatic hydrocarbons (in Chinese with English abstract). *J Earth Sci* 31:873–878
- Li J, Wang YR, Li KF, Rui JL (2006) Eco-hydraulics method of calculating the lowest ecological water demand in river channels (in Chinese with English abstract). *J Hydraul Eng* 37:1169–1174
- Li Y, Liang Q, Cai C, Qin L, Xiao G (2012) Investigation of iodine in salt, water and urine in Maoming (in Chinese with English abstract). *Guangdong Trace Elem Sci* 19:5–9
- Li B, Jiang Y, Zhong G, Qiu Y, Chen J (2013) The investigation of groundwater iodine and residents iodine nutrition at Meizhou in 2012 (in Chinese with English abstract). *Chin R Health* 3:10–11
- Li J, Wang Y, Guo W, Xie X, Zhang L, Liu Y, Kong S (2014a) Iodine mobilization in groundwater system at Datong basin, China: evidence from hydrochemistry and fluorescence characteristics. *Sci Total Environ* 468:738–745
- Li J, Li F, Liu Q, Suzuki Y (2014b) Nitrate pollution and its transfer in surface water and groundwater in irrigated areas: a case study of the piedmont of south Taihang Mountains, China. *Environ Sci Process Impacts* 16:2764–2773
- Li J, Li F, Liu Q, Zhang Y (2014c) Trace metal in surface water and groundwater and its transfer in a Yellow River alluvial fan: evidence from isotopes and hydrochemistry. *Sci Total Environ* 472:979–988
- Li L, Wu Y, Wang YX, Pi K, Liu P, Li JX (2014) Fluorine speciation in sediments from endemic fluorosis-impacted areas in Datong Basin (in Chinese with English abstract). *Saf Environ Eng* 21(5):52–57
- Li J, Pu L, Han M, Zhu M, Zhang R, Xiang YZ (2014e) Soil salinization research in China: advances and prospects. *J Geogr Sci* 24(5):943–960
- Li J, Liu H, Su Z, Fan X (2015) Changes in wind activity from 1957 to 2011 and their possible influence on aeolian desertification in northern China. *J Arid Land* 7:755–764
- Li J, Wang Y, Xie X (2016a) Cl/Br ratios and chlorine isotope evidences for groundwater salinization and its impact on groundwater arsenic, fluoride and iodine enrichment in the Datong basin, China. *Sci Total Environ* 544:158–167
- Li J, Wang Y, Xie X, Depaolo DJ (2016b) Effects of water-sediment interaction and irrigation practices on iodine enrichment in shallow groundwater. *J Hydrol* 543:293–304
- Li S, Birk S, Xue L, Ren H, Chang J, Yao X (2016c) Seasonal changes in the soil moisture distribution around bare rock outcrops within a karst rocky desertification area (Fuyuan County, Yunnan Province, China). *Environ Earth Sci* 75:1482
- Li S, Cheng J, Li M, Cui L (2016d) Water quality characteristics and evolution of groundwater system influenced by human exploitation activity in Hengshui area (in Chinese with English abstract). *South-North Water Transf Water Sci Technol* 14:55–60
- Li C, Liu T, Xu S, Gao X, Wang Y (2016e) Groundwater salinization in shallow aquifers adjacent to a low-altitude inland salt lake: a case study at Yuncheng Basin, northern China. *Environ Earth Sci* 75:370
- Li X, Tang C, Han Z, Cao Y (2016f) Hydrochemical characteristic and interaction process of surface and groundwater in mid-lower reach of Hanjiang River, China. *Environ Earth Sci* 75:418
- Li P, Tian R, Xue C, Wu J (2017) Progress, opportunities, and key fields for groundwater quality research under the impacts of human activities in China with a special focus on western China. *Environ Sci Pollut Res Int* 24:13224–13234
- Li J, Zhou H, Qian K, Xie X, Xue X, Yang Y, Wang Y (2017a) Fluoride and iodine enrichment in groundwater of North China plain: evidences from speciation analysis and geochemical modeling. *Sci Total Environ* 598:239–248
- Li J, Li F, Liu Q (2017b) PAHs behavior in surface water and groundwater of the Yellow River estuary: evidence from isotopes and hydrochemistry. *Chemosphere* 178:143–153
- Liang P, Ren J (2005) Investigation of IQ status of 1632 children (8–10 year old) at Xuzhou in 2000 (in Chinese). *End Dis Bull* 20:111–111
- Liang B, Wang C, Wang PF, Qian J, Zheng XY (2003) Impacts of river wastewater unsaturated infiltration on its offshore soil and

- groundwater quality (in Chinese with English abstract). *Adv Water Sci* 14:548–553
- Lin XY, Wang Y (eds) (2017) *Groundwater science*. Science Press, Beijing
- Lin ML, Peng WH, Gui HR (2016) Hydrochemical characteristics and quality assessment of deep groundwater from the coal-bearing aquifer of the Linhuan coal-mining district, northern Anhui Province, China. *Environ Monit Assess* 188:202
- Liu JC (2009) Investigation on iodine concentration in drinking water in the areas south of Yellow River in Binzhou City in 2008. *Prev Med Tribune* 15(8):691–692
- Liu D, Chen Q, Yu Z (1980) Geochemical environment problems concerning the endemic fluorine disease in China (in Chinese with English abstract). *Geochimica* 33:13–22
- Liu C, Yu J, Eloise K (2001) Groundwater exploitation and its impact on the environment in the North China plain. *Water Int* 26:265–272
- Liu J, Zheng C, Zheng L, Lei Y (2008) Ground water sustainability: methodology and application to the North China plain. *Groundwater* 46:897–909
- Liu Q, Li F, Zhang Q, Li J, Zhang Y, Tu C, Ouyang Z (2014) Impact of water diversion on the hydrogeochemical characterization of surface water and groundwater in the Yellow River Delta. *Appl Geochem* 48:83–92
- Liu F, Zhang H, Qin Y, Dong J, Xu E, Yang Y, Zhang G, Xiao X (2016a) Semi-natural areas of Tarim Basin in Northwest China: linkage to desertification. *Sci Total Environ* 573:178–188
- Liu S, Gao M, Tang Z, Hou G, Guo F (2016b) Responses of submarine groundwater to silty-sand coast reclamation: a case study in south of Laizhou Bay, China. *Estuar Coast Shelf Sci* 181:51–60
- Long H, Zhu Q, Tian P, Hu W (2015) Technologies and applications of geophysical exploration in deep geothermal resources in China. In: *Proceedings World Geothermal Congress 2015*, Melbourne, Australia, April 2015
- Lu T, He G, Wang J, Zhang M (2011) Investigation on distribution of high iodine region and its epidemiology in the city of Xinxiang (in Chinese with English abstract). *Chin J Cont End Dis* 26:203–205
- Lu C, Zhao T, Shi X, Cao S (2016) Ecological restoration by afforestation may increase groundwater depth and create potentially large ecological and water opportunity costs in arid and semiarid China. *J Cleaner Product* 176:1213–1222
- Luo W, Zhang X, Gao X (2017) Impact of human activities on environmental fluoride pollution in Yuncheng Basin (in Chinese). *Saf Environ Eng* 24(2):46–52
- Ma R (2012) Current situation of Chinese groundwater monitoring network (in Chinese). *Agric Technol* 32(5):20–22
- Ma H (2016) Major ion chemistry of groundwater in the Sangong River watershed, northwestern China. *Environ Earth Sci* 75:1–17
- Ma T, Wang Y, Yan S, Ma R, Yan C, Zhou X (2005) Causes of land subsidence in Taiyuan city, Shanxi, China land subsidence. *Proceedings of the Seventh International Symposium on Land Subsidence*, Shanghai, October 2005
- Ma R, Wang Y, Ma T, Sun Z, Yan S (2006) The effect of stratigraphic heterogeneity on areal distribution of land subsidence at Taiyuan, northern China. *Environ Geol* 50:551–568
- Ma F, Yang YS, Yuan R, Cai Z, Pan S (2007) Study of shallow groundwater quality evolution under saline intrusion with environmental isotopes and geochemistry. *Environ Geol* 51:1009–1017
- Ma W, Mao Z, Yu Z, Mensvoort MEFV, Driessen PM (2008) Effects of saline water irrigation on soil salinity and yield of winter wheat-maize in North China plain. *Irrig Drainag Syst* 22(1):3–18
- Ma L, Lowenstein TK, Li B, Jiang P, Liu C, Zhong J, Sheng J, Qiu H, Wu H (2010) Hydrochemical characteristics and brine evolution paths of lop nor basin, Xinjiang Province, western China. *Appl Geochem* 25:1770–1782
- Ma J, Pan F, He J, Chen L, Fu S, Jia B (2012) Petroleum pollution and evolution of water quality in the Malian River basin of the Longdong loess plateau, northwestern China. *Environ Earth Sci* 66:1769–1782
- Ma F, Wei A, Deng Q, Zhao H (2015) Hydrochemical characteristics and the suitability of groundwater in the coastal region of Tangshan, China. *J Earth Sci* 25:1067–1075
- Mainguet M (1991) *Desertification*. Springer, Berlin
- Mclaughlin D, Kinzelbach W (2015) Food security and sustainable resource management. *Water Resour Res* 51(7):4966–4985
- Ministry of Ecology and Environment of the People's Republic of China (2011) National groundwater pollution and control plan (2011–2020). http://www.gov.cn/gongbao/content/2012/content_2121713.html. Accessed May 2018
- Ministry of Water Resources of the People's Republic of China (2015) China Water Resources Bulletin. http://www.mwr.gov.cn/sj/tjgb/szygb/201612/t20161229_783348.html. Accessed May 2018
- Mo G, Huiqing X (2005) Investigation on iodine concentration in drinking water in Jiaxing (in Chinese). *Zhejiang J Prev Med* 17:27–27
- National Health and Family Planning Commission of China (2016) *Statistical review of Chinese health and family planning*. Beijing Union Medical University Press, Beijing
- Norra S, Berner ZA, Agarwala P, Wagner F, Chandrasekharam D, Stüben D (2005) Impact of irrigation with as rich groundwater on soil and crops: a geochemical case study in West Bengal Delta plain, India. *Appl Geochem* 20:1890–1906
- Pan YL, Su CL, Wang YX, Wu X (2013) Distribution characteristics and controlling factors of fluorine content in sediments of Shanyin-Ying county, Datong Basin, northern China (in Chinese with English abstract). *J Mineral Petrol* 33(2):109–114
- Pei H, Scanlon BR, Shen Y, Reedy RC, Long D, Liu C (2015) Impacts of varying agricultural intensification on crop yield and groundwater resources: comparison of the North China plain and US High Plains. *Environ Res Lett* 10:1–25
- Qiu J (2010) China faces up to groundwater crisis. *Nature* 466:308
- Ren F, Jiao S (1988) Distribution and formation of high-fluorine groundwater in China. *Environ Geol Water Sci* 12:3–10
- Ren F, Zeng J, Liu W, Zhang C (1996) Hydrogeochemical environment of high fluorine groundwater and the relation between the speciation of fluorine and the diseased ratio of endemic fluorosis: a case study of the North China Plain (in Chinese with English abstract). *Acta Geosci Sin* 17(1):85–97
- Reynolds JF, Smith DMS (2002) *Global desertification: do humans cause deserts?* Dahlem University Press, Berlin
- Rodríguezlazo L, Sun G, Berg M, Zhang Q, Xue H, Zheng Q, Johnson CA (2013) Groundwater arsenic contamination throughout China. *Science* 341:866–868
- Rohden CV, Kreuzer A, Chen Z, Kipfer R, Aeschbach-Hertig W (2010) Characterizing the recharge regime of the strongly exploited aquifers of the North China plain by environmental tracers. *Water Resour Res* 46:2621–2628
- Ruan Z, Yu B, Wang L, Pan Y, Tan G (2013) Prediction of buried calcite dissolution in the Ordovician carbonate reservoir of the Tahe oilfield, NW China: evidence from formation water. *Chemie der Erde Geochem* 73:469–479
- Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM, Simmers I (2006) Global synthesis of groundwater recharge in semi-arid and arid regions. *Hydrol Process* 20:3335–3370
- Schaefer MV, Ying SC, Benner SG, Duan Y, Wang Y, Fendorf S (2016) Aquifer arsenic cycling induced by seasonal hydrologic changes within the Yangtze River basin. *Environ Sci Technol* 50:3521–3529
- Schaefer MV, Guo X, Gan Y, Benner SG, Griffin AM, Gorski CA, Wang Y, Fendorf S (2017) Redox controls on arsenic enrichment and release from aquifer sediments in central Yangtze River basin. *Geochim Cosmochim Acta* 204:104–119
- Schilling OS, Doherty J, Kinzelbach W, Wang H, Yang PN, Brunner P (2014) Using tree ring data as a proxy for transpiration to reduce

- predictive uncertainty of a model simulating groundwater–surface water–vegetation interactions. *J Hydrol* 519:2258–2271
- Shen Z, Guo H, Xu G, Wang C (2010) Abnormal groundwater chemistry and endemic disease (in Chinese). *Chin J Nat* 32(2):83–89
- Shen B, Xiao S, Bao H, Kaufman AJ, Zhou C, Yuan X (2011) Carbon, sulfur, and oxygen isotope evidence for a strong depth gradient and oceanic oxidation after the Ediacaran Hanksalchough glaciation. *Geochim Cosmochim Acta* 75:1357–1373
- Shetaya WH, Young SD, Watts MJ, Ander EL, Bailey EH (2012) Iodine dynamics in soils. *Geochim Cosmochim Acta* 77:457–473
- Shi XQ, Xue YQ, Ye SJ, Wu JC, Zhang Y, Yu J (2007) Characterization of land subsidence induced by groundwater withdrawals in Su-xi-Chang area, China. *Environ Geol* 52:27–40
- Shi X, Xue Y, Wu J, Ye S, Zhang Y, Wei Z, Yu J (2008) Characterization of regional land subsidence in Yangtze Delta, China: the example of Su-xi-Chang area and the city of Shanghai. *Hydrogeol J* 16:593–607
- Shimamoto YS, Takahashi Y, Terada Y (2011) Formation of organic iodine supplied as iodide in a soil–water system in Chiba, Japan. *Environ Sci Technol* 45:2086–2092
- Smedley PL, Zhang M, Zhang G, Luo Z (2003) Mobilisation of arsenic and other trace elements in fluvio-lacustrine aquifers of the Huhhot Basin, Inner Mongolia. *Appl Geochem* 18:1453–1477
- Song X (2010) Modeling application in evaluating groundwater–surface water interactions due to phosphate mining activities. *Hydrogeol Regulatory Environ Phosphate Mining Process* 42(5):548–548
- Song C, Deng W (2000) Characters of groundwater and influence on the interior salt-affected soil in the west of Jilin Province (in Chinese with English abstract). *Sci Geogr Sin* 20:246–250
- Sracek O, Wanke H, Ndakunda NN, Mihaljevič M, Buzek F (2015) Geochemistry and fluoride levels of geothermal springs in Namibia. *J Geochem Explor* 148:96–104
- Su LT, Zhang ZY, Song YD, Yu MT (2005) Study on soil desertification in response to groundwater level and its prediction model in the lower reaches of Tarim River (in Chinese with English Abstract). *J Arid Land Resour Environ* 9(3):107–112
- Su H, Kang T, Zhang Y, Ye J, Ke J (2006) The investigation of iodine concentration in groundwater at Xiamen (in Chinese). *J Environ Health* 23:532
- Sun ZY, Ma T, Ma J, Ma R, Yan CM (2007) Effect of strata heterogeneity on spatial pattern of land subsidence in Taiyuan City. *Yantu Lixue/Rock Soil Mech* 28:399–408
- Sun Z, Long X, Ma R (2016a) Water uptake by saltcedar (*Tamarix ramosissima*) in a desert riparian forest: responses to intra-annual water table fluctuation. *Hydrol Process* 30:1388–1402
- Sun Z, Ma R, Wang Y, Hu Y, Sun L (2016b) Hydrogeological and hydrogeochemical control of groundwater salinity in an arid inland basin: Dunhuang Basin, northwestern China. *Hydrol Process* 30:1884–1902
- Sun Z, Ma R, Wang Y, Ma T, Liu Y (2016c) Using isotopic, hydrogeochemical-tracer and temperature data to characterize recharge and flow paths in a complex karst groundwater flow system in northern China. *Hydrogeol J* 24:1–20
- Tan J (1989) The atlas of endemic diseases and their environments in the People's Republic of China (in Chinese). Science Press, Beijing
- Tang QC (1995) The development in oases and rational use of water resources (in Chinese with English abstract). *J Arid Land Resour Environ* 9(3):107–112
- Tang QC, Zhang JB (2011) Water resources and eco environment protection in the arid regions in northwest of China (in Chinese with English abstract). *Prog Geogr* 20:227–233
- Tang ZC, Jiang XK, Liang W, Zhang L (2006) Investigation on the distribution of high iodine region and inhabitant iodine nutritional status in the city of Liaocheng (in Chinese with English abstract). *Chin J Endemiol* 25:683–685
- Tang Q, Xu Q, Zhang F, Huang Y, Liu J, Wang X, Yang Y, Liu X (2013) Geochemistry of iodine-rich groundwater in the Taiyuan Basin of Central Shanxi Province, North China. *J Geochem Explor* 135:117–123
- Taylor RG, Scanlon B, Döll P, Rodell M, Beek RV, Wada Y, Longuevergne L, Leblanc M, Famiglietti JS, Edmunds M (2013) Ground water and climate change. *Nat Clim Chang* 3:322–329
- Tufano KJ, Fendorf S (2008) Confounding impacts of iron reduction on arsenic retention. *Environ Sci Technol* 42:4777–4783
- Tursun K, Shi L, Han G, Mannisaguli T (2008) Response of vegetation and desertification to groundwater change due to emergency water supply in lower reaches of Tarim River (in Chinese with English abstract). *J Desert Res* 28:1033–1038
- Vithanage M, Bhattacharya P (2015) Fluoride in the environment: sources, distribution and defluoridation. *Environ Chem Lett* 13:131–147
- Wan JT, Hao QC, Gong GR, Chen SU, Cui YL, Liu Q (2013) Distribution and genesis of high-fluorine groundwater in southwestern Shandong Province (in Chinese with English abstract). *Geoscience* 27:448–453
- Wang YX (2007) Groundwater contamination (in Chinese). Higher Education Press, Beijing
- Wang QR (2010) Studies of numerical simulation of the water quality and quantity transport under sea surface water and groundwater interaction. Master MSc Thesis, China University of Geosciences, Beijing
- Wang Y (2016) Numerical simulation of regional land subsidence in coastal area of North Jiangsu (in Chinese with English abstract). MSc Thesis, Nanjing University, Nanjing, China
- Wang G, Cheng G (2001) Fluoride distribution in water and the governing factors of environment in arid north-West China. *J Arid Environ* 49:601–614
- Wang Y, Jiao JJ (2012) Origin of groundwater salinity and hydrogeochemical processes in the confined Quaternary aquifer of the Pearl River Delta, China. *J Hydrol* 438–439:112–124
- Wang X, Kawahara, Guo XJ (1999) Fluoride contamination of groundwater and its impacts on human health in Inner Mongolia area. *Aqua* 48:146–153
- Wang W, Luan Y, Yang Z, Qiao X, Yang X (2001) Influence on water resource and eco-environment system of Geermu alluvial fan by great artificial projects (in Chinese with English abstract). *J Xian Eng Univ*
- Wang G, Yang L, Chen L, Kubota J (2005) Impacts of land use changes on groundwater resources in the Heihe River basin (in Chinese with English abstract). *Acta Geograph Sin* 60:456–466
- Wang JX, Huang JK, Blanke A, Huang QQ, Rozelle S, Giordano M, Villholth KG (2007) The development, challenges and management of groundwater in rural China. In: Giordano M, Villholth KG (eds) The agricultural groundwater revolution-Opportunities and threats to development, chap 3. International Water Management Institute, Colombo, Sri Lanka, pp 37–62
- Wang YX, Shvartsev SL, Su CL, Evans WC (2009) Genesis of arsenic/fluoride-enriched soda water: a case study at Datong, northern China. *Appl Geochem* 24:641–649
- Wang Y, Chen ZY, Fei YH, Liu J, Wei W (2011) Estimation of water released from aquitard compaction indicated by fluorine in Cangzhou (in Chinese with English abstract). *J Jilin Univ* 41:298–302
- Wang J, Gao W, Xu S, Yu L (2012) Evaluation of the combined risk of sea level rise, land subsidence, and storm surges on the coastal areas of Shanghai, China. *Clim Chang* 115:537–558
- Wang P, Yu J, Zhang Y, Liu C (2013a) Groundwater recharge and hydrogeochemical evolution in the Ejina Basin, Northwest China. *J Hydrol* 476:72–86
- Wang T, Yan CZ, Song X, Li S (2013b) Landsat images reveal trends in the aeolian desertification in a source area for sand and dust storms in China's Alashan plateau (1975–2007). *Land Degrad Dev* 24:422–429

- Wang S, Tang C, Song X, Wang Q, Zhang Y, Yuan R (2014) The impacts of a linear wastewater reservoir on groundwater recharge and geochemical evolution in a semi-arid area of the Lake Baiyangdian watershed, North China plain. *Sci Total Environ* 482–483:325–335
- Wang J, Gao Y, Wang S (2015a) Land use/cover change impacts on water table change over 25 years in a desert-oasis transition zone of the Heihe River basin, China. *Water* 8:11
- Wang X, Zhou X, Zhao J, Zheng Y, Song C, Long M, Chen T (2015b) Hydrochemical evolution and reaction simulation of travertine deposition of the Lianchangping hot springs in Yunnan, China. *Quat Int* 374:62–75
- Wang JZ, Wu JL, Jia HJ (2016a) Analysis of spatial variation of soil salinization using a hydrochemical and stable isotopic method in a semiarid irrigated basin, Hetao plain, Inner Mongolia, North China. *Environ Proc* 3:723–733
- Wang S, Tang C, Song X, Yuan R, Han Z, Pan Y (2016b) Factors contributing to nitrate contamination in a groundwater recharge area of the North China plain. *Hydrol Process* 30:2271–2285
- Wang X, Lin L, Kong M, Cheng H (2016c) Chinese hydrogeochemical investigation report. Chinese Geological Survey, Beijing. http://www.cgs.gov.cn/ddzt/cgs100/bxcg/tdkjcx/201611/t20161125_417837.html. Accessed May 2018
- Wei L (1992) Development of arsenic mineral resources and environment control (in Chinese with English Abstract). *Hunan Geol* 11(3):259–262
- Wei C, Guo H, Zhang D, Wu Y, Han S, An Y, Zhang F (2016a) Occurrence and hydrogeochemical characteristics of high-fluoride groundwater in Xiji County, southern part of Ningxia Province, China. *Environ Geochem Health* 38:275–290
- Wei M, Liu W, Bai F, Zhang M (2016b) Progress in the research of environmental monitoring of groundwater at home and abroad (in Chinese with English abstract). *Environ Protect Sci* 42(5):15–18
- Wen D, Zhang F, Zhang E, Wang C, Han S, Zheng Y (2013) Arsenic, fluoride and iodine in groundwater of China. *J Geochem Explor* 135:1–21
- Werner AD, Zhang Q, Xue L, Smerdon BD, Li X, Zhu X, Yu L, Li L (2013) An initial inventory and indexation of groundwater mega-depletion cases. *Water Resour Manag* 27:507–533
- Williams MAJ, Balling RC, Jr (2005) Interactions of desertification and climate. Arnold, London
- Xie JZ (2004) Water resources problems and water-saving strategies in Hexi corridor. *J Desert Res* 24:802–803
- Xie Z, Zhang C, Han D, Zhang M (2005) Investigation of iodine concentration in drinking water at Jinan (in Chinese). *Chin J Public Health Manag*
- Xie X, Wang Y, Li J, Su C, Duan M (2013) Hydrogeochemical and isotopic investigations on groundwater salinization in the Datong Basin, northern China. *JAWRA* 49:402–414
- Xu B, Wang G (2016) Surface water and groundwater contaminations and the resultant hydrochemical evolution in the Yongxiu area, west of Poyang Lake, China. *Environ Earth Sci* 75:184
- Xu F, Ma T, Shi L, Dong Y, Liu L, Zhong X, Wang Y (2012) Hydrogeochemical characteristics of high iodine groundwater in the Hetao plain, Inner Mongolia (in Chinese with English abstract). *Hydrogeol Eng Geol* 39:8–15
- Xue Y, Wu J, Ye S, Zhang Y (2000) Hydrogeological and hydrogeochemical studies for salt water intrusion on the south coast of Laizhou Bay, China. *Ground Water* 38:38–45
- Xue YQ, Zhang Y, Ye SJ, Wu JC, Li QF (2005) Land subsidence in China. *Environ Geol* 48:713–720
- Yan S, Ma R, Wang YX (2006) The effect of tectonic activity on land subsidence in Taiyuan (in Chinese). *Earth Sci-J Chin Univ Geosci* 31:120–125
- Yan Q, Zhu J, Zheng X, Jin C (2015) Causal effects of shelter forests and water factors on desertification control during 2000–2010 at the Horqin Sandy land region, China (in Chinese with English abstract). *J Forest Res (Eng edn.)* 26:33–45
- Yang Z (2006) Ecological water consumption pattern of watershed (in Chinese). Science Press, Beijing
- Yang XT (2011) Mechanism study on contaminant transport in river-groundwater system during riverside pumping (in Chinese with English abstract). PhD Thesis, Chang'an University, Beilin, China
- Yang X, Zhang K, Jia B, Ci L (2005) Desertification assessment in China: an overview. *J Arid Environ* 63:517–531
- Yang L, Song X, Zhang Y, Han D, Zhang B, Long D (2012a) Characterizing interactions between surface water and groundwater in the Jialu River basin using major ion chemistry and stable isotopes. *Hydrol Earth Syst Sci* 9:5955–5981
- Yang Y, Li GM, Dong YH, Li M, Yang JQ, Zhou D, Yang ZS, Zheng FD (2012b) Influence of south to north water transfer on groundwater dynamic change in Beijing plain. *Environ Earth Sci* 65:1323–1331
- Yang X, Chen Y, Pacenka S, Gao W, Zhang M, Sui P, Steenhuis TS (2015) Recharge and groundwater use in the North China plain for six irrigated crops for an eleven year period. *PLoS One* 10:e0115269
- Ye A, Duan Q, Chu W, Xu J, Mao Y (2015) The impact of the south-north water transfer project (CTP)'s central route on groundwater table in the Hai River basin, North China. *Hydrol Process* 28:5755–5768
- Yi L, Fang Z, He X, Chen S, Wei W, Qiang Y (2011) Land subsidence in Tianjin, China. *Environ Earth Sci* 62:1151–1161
- Yu G, Sun D, Zheng Y (2007) Health effects of exposure to natural arsenic in groundwater and coal in China: an overview of occurrence. *Environ Health Perspect* 115:636–642
- Yuan C (1964) Determination of groundwater critical depth (in Chinese). *J Hydraul Eng* 3:53–55
- Yuan DX (1997) Rock desertification in the subtropical karst of South China. *Geomorphology* 108:81–90
- Yuan LR, Xin P, Kong J, Li L, Lockington D (2011) A coupled model for simulating surface water and groundwater interactions in coastal wetlands. *Hydrol Process* 25:3533–3546
- Zhang GX (2004) Discussion of strategies for sustainable water resource utilization on Songnen plain. *Bull Soil Water Conserv* 24(1):69–73
- Zhang SQ, Wang YG, Zhu H, Cao WB, Shi WD, Huang Y, Yong Guo LI (2003) Changes in water environment and their ecologicgeologic environmental effects in the headwater area of the Yellow River. *Hydrogeol Eng Geol* 30:11–14
- Zhang Z, Zhang G, Ren H, Fei J (2006) The evolution of regional groundwater and its interaction with adjacent spheres (in Chinese). Geological Publishing House, Beijing
- Zhang G, Deng W, Yang YS, Salama RB (2007) Evolution study of a regional groundwater system using hydrochemistry and stable isotopes in Songnen plain, Northeast China. *Hydrol Process* 21:1055–1065
- Zhang Y, Xue YQ, Wu JC, Yu J, Wei ZX, Li QF (2008) Land subsidence and earth fissures due to groundwater withdrawal in the southern Yangtse Delta, China. *Environ Geol* 55:751
- Zhang EY, Zhang FC, Qian Y, Ye NJ, Gong JS, Wang YS (2010) The distribution of high iodine groundwater in typical areas of China and its inspiration (in Chinese with English abstract). *Geol China* 37: 797–802
- Zhang E, Wang Y, Qian Y, Ma T, Zhang D, Zhan H, Zhang Z, Fei Y, Wang S (2013a) Iodine in groundwater of the North China plain: spatial patterns and hydrogeochemical processes of enrichment. *J Geochem Explor* 135:40–53
- Zhang S, Xu C, Creeley D, Ho YF, Li HP, Grandbois R, Schwehr KA, Kaplan DI, Yeager CM, Wellman D (2013b) Iodine-129 and iodine-127 speciation in groundwater at the Hanford site, US: iodate incorporation into calcite. *Environ Sci Technol* 47:9635–9642
- Zhang B, Song X, Zhang Y, Han D, Tang C, Yang L, Wang ZL (2015a) The relationship between and evolution of surface water and groundwater in Songnen plain, Northeast China. *Environ Earth Sci* 73:8333–8343

- Zhang F, Tiyip T, Johnson VC, Kung H, Ding J, Zhou M, Fan Y, Kelimu A, Nurmhammat I (2015b) Evaluation of land desertification from 1990 to 2010 and its causes in Ebinur Lake region, Xinjiang China. *Environ Earth Sci* 73:5731–5745
- Zhang W, Chen X, Tan H, Zhang Y, Cao J (2015c) Geochemical and isotopic data for restricting seawater intrusion and groundwater circulation in a series of typical volcanic islands in the South China Sea. *Mar Pollut Bull* 93:153–162
- Zhang B, Song X, Zhang Y, Ying MA, Tang C, Yang L, Wang ZL (2016a) The interaction between surface water and groundwater and its effect on water quality in the second Songhua River basin, Northeast China. *J Earth Syst Sci* 125:1–13
- Zhang X, Li X, Gao X (2016b) Hydrochemistry and coal mining activity induced karst water quality degradation in the Niangziguan karst water system, China. *Environ Sci Pollut Res Int* 23:6286–6299
- Zhang B, Song X, Zhang Y, Han D, Tang C, Yang L, Wang ZL (2017) The renewability and quality of shallow groundwater in Sanjiang and Songnen plain, Northeast China. *J Int Agricul (Engl. edn.)* 16: 229–238
- Zhao TM, Li YS (2015) Groundwater quality degradation influencing factors in intensive cropping area (in Chinese with English abstract). *J Anhui Agric Sci* 43(17):115–119
- Zhao C, Wang Y, Chen X, Li B (2005) Simulation of the effects of groundwater level on vegetation change by combining FEFLOW software. *Ecol Model* 187:341–351
- Zhao L, Wu S, Zhou J, Wang J (2007) Eco-geochemical investigation on the endemic As and F poisoning in Datong Basin (in Chinese with English abstract). *Earth Sci Front* 14(2):225–235
- Zhao H, Xu C, Chen G, Wang X, Sun F, Wang X (2014) Investigation of iodine concentration in drinking water and residents iodine nutrition at Shangqiu (in Chinese). *Contemp Med* 20:162–163
- Zhao J, Lin J, Wu J, Yang Y, Wu J (2016a) Numerical modeling of seawater intrusion in Zhoushuizi district of Dalian City in northern China. *Environ Earth Sci* 75:1–18
- Zhao Z, Wu J, Yuan G, Chen J, Xu X, Yan C, Bai Y (2016b) Hydrochemical investigation of shallow groundwater in northwest margin of Lop Nur, Northwest China. *Environ Earth Sci* 75:214
- Zheng C, Liu J (2013) China's "Love Canal" moment? *Science* 340:810
- Zheng C, Liu J, Cao G, Kendy E, Wang H, Jia Y (2010) Can China cope with its water crisis? Perspectives from the North China plain. *Ground Water* 48:350–354
- Zheng Q, Ma T, Wang Y, Yan Y, Liu L, Liu L (2017) Hydrochemical characteristics and quality assessment of shallow groundwater in Xincai River basin, northern China. *Proced Earth Planet Sci* 17: 368–371
- Zhong HP, Liu H, Wang Y, Ya T, Geng LH, Yan ZJ (2002) Relationship between Ejina oasis and water resources in the lower Heihe River basin (in Chinese with English abstract). *Adv Water Sci* 13:223–228
- Zhou G, Wei X, Wu Y, Liu S, Huang Y, Yan J, Zhang D, Zhang Q, Liu J, Meng Z (2011) Quantifying the hydrological responses to climate change in an intact forested small watershed in southern China. *Glob Chang Biol* 17:3736–3746
- Zhou J, Zhang Y, Zhou A, Liu C, Cai H, Liu Y (2016) Application of hydrochemistry and stable isotopes ($\delta^{34}\text{S}$, $\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$) to trace natural and anthropogenic influences on the quality of groundwater in the piedmont region, Shijiazhuang, China. *Appl Geochem* 71:63–72
- Zhu J, Hu K, Lu X, Huang X, Liu K, Wu X (2015a) A review of geothermal energy resources, development, and applications in China: current status and prospects. *Energy* 93:466–483
- Zhu L, Gong H, Li X, Wang R, Chen B, Dai Z, Teatini P (2015b) Land subsidence due to groundwater withdrawal in the northern Beijing plain, China. *Eng Geol* 193:243–255