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Original Research

How Rapid Urbanization Drives Deteriorating Groundwater Quality in a Provincial Capital of China

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Abstract

Groundwater monitoring and social-economic development data were collected to explore the effect of rapid urbanization on groundwater environment and quality. The results show that the groundwater table continuously declined from 13.96 m to 43.25 m between 1972 and 2015. Groundwater hydrochemistry in the Shijiazhuang area changed from a HCO_3-Ca (Mg) to HCO_3. SO_4-Ca (Mg) type, becoming more diverse and complex. Groundwater environments have changed, caused by the oxidation-reduction environment changing, the vadose zone thickening, and the proportion of impervious surface area sincreasing. Groundwater quality has deteriorated significantly and NO_3^- and hardnes shave exceeded grade III of the Chinese national groundwater quality standard range. The concentrations of Cl^-, Mg^{2+}, NO_3^-, salinity and hardness significantly correlate with gross domestic product, permanent population, and population density. The driving factors causing groundwater quality deterioration are population growth, social and economic development, and over-exploitation of groundwater. Therefore, the state and the administration are trying to protect the groundwater environment while pursuing a rapid socioeconomic development.

Keywords: urbanization; groundwater hydrochemistry; groundwater quality; driving factors

Introduction

Urbanization is a necessary stage of human civilization progress. More than half of the world's population now lives in cities due to rapid urbanization [1]. As the largest developing country in the world, China has been undergoing rapid urbanization since the Chinese economic reform in 1978 [2] and the process has become a primary driving force of China's economic and social development[3].

Urbanization is a "double-edged sword" as it accelerates a nation's economic growth and improves people's standard of living, but also leads to severe environmental pollution [4, 5]. Previous studies have

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found that rapid urbanization affects the atmospheric environment [5-7], energy use and CO_2 emissions [8, 9], land use and land cover change [10, 11], water resources [12]. However, few studies have considered the relationship between urbanization and groundwater quality.

In China, groundwater accounts for one-third of total water use across the domestic, agricultural, and industrial sectors, and approximately two-thirds of cities utilize groundwater as a primary water supply. Currently, with rapid urbanization,groundwater pollution is becoming increasingly severe, and anthropogenic groundwater contamination has attracted attention [13, 14]. Qiu [15] has reported that 90% of China's shallow groundwater is polluted, according to the Ministry of Land and Resources, and an alarming 37% is so foul that it cannot be treated for use as drinking water. Rodríguez-Lado et al.[14]has suggested that more than 19 million Chinese are at risk of being affected by the consumption of arsenic-contaminated groundwater. According to the latest Bulletin of Land and Resources of Chinain 2014, groundwater from 61.5% of 4896 monitoring wells in 202 cities across China have been characterized as poor (IV class) or very poor (V class), according to China's 5-class groundwater quality rating standard.

The key step in effectively controlling groundwater pollution is identifying the interaction mechanism between urbanization and groundwater quality. However, such work has not been reported. This shortcoming has influenced decision makers in setting control measures on groundwater water quality deterioration. This study expands on previous work, choosing Shijiazhuang city as a representative of rapid urbanization and using large time-scale data from 1986 to 2014. Shijiazhuang is the capital of Hebei Province, and it is located in the piedmont of Taihang Mountain in the southwestern sector of the province. In recent decades, Shijiazhuang has experienced rapid urbanization. According to the Shijiazhuang Statistical Yearbook 1995 and 2014, the urbanization rate and urban population increased from 21.04% and 1.8×10^6 to 56.17% and 6.0×10^6, respectively. The areas of cultivated land and forest decreased from 5990 km^2 and 4620 km^2, respectively, to 5287 km^2 and 3233 km^2, respectively, while the area of land within the city increased from 85 km^2 to 264 km^2.

Concurrently, groundwater has been heavily extracted and the groundwater table has dropped rapidly (Fig. 1), even forming regional groundwater depression cones. In addition, several studies have found that the shallow groundwater quality has deteriorated in this region [16, 17], despite being the main source of industrial, agricultural, and drinking water, and directly influencing daily life.

The main aims of the study are to 1) identify the temporal evolution of urbanization and groundwater quality, 2) analyze the effect of rapid urbanization on groundwater table and quality, 3) discuss the mechanisms of groundwater quality deterioration, and

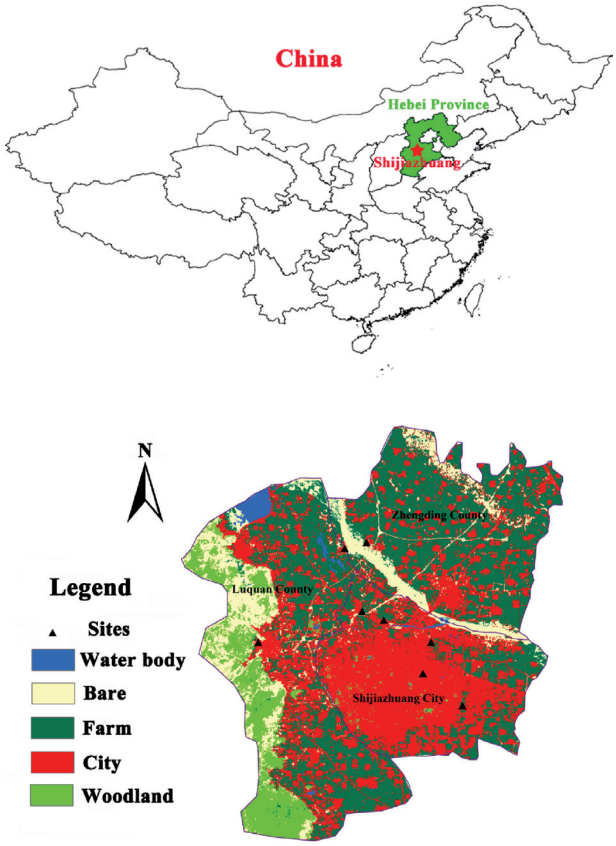

Fig. 1. Water quality monitoring sites and land use of Shijiazhuang.

4) identify the main factors in groundwater quality contamination due to rapid urbanization by using principal component analysis (PCA).

Materials and Methods

Study Area

Shijiazhuangis located in south-central Hebei Province, and as the capital city of the province it belongs to the Bohai economic circle (Fig. 1). It lies on East Taihang Mountain and the western edge of the North China Plain, between 113°30′E-115°29′E and 37°27′N-38°45′N). Transportation within the study area is convenient, including the Jing-Guang railroad plus Shi-Tai and Jing-Shen expressways, which guarantee rapid economic construction in the region. Since the reform and opening, an economic structure has formed with agriculture as the foundation, guided by industry, and a balance of first, second and third industry development.

The study area is in a temperate monsoon climate, with distinctive seasons and concentrated rainfall. The lowest temperatures occur in January, averaging about 1ºC. The temperature began to rise rapidly in April and highest annual temperatures occur in July, averaging

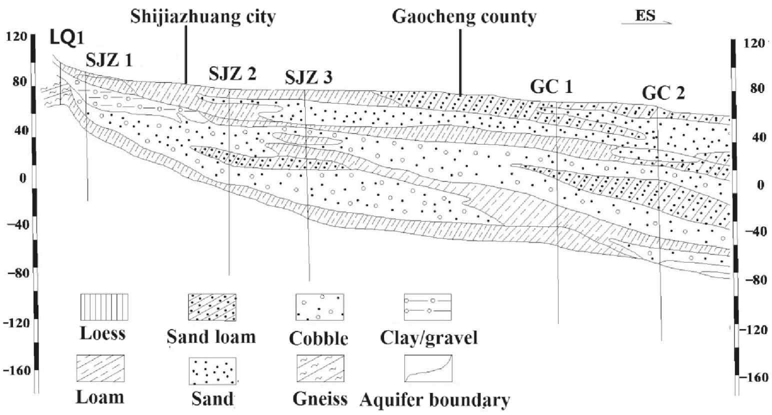

Fig. 2. Hydrogeological cross-section of Shijiazhuang city.

25ºC. The spatial and temporal distribution of rainfall in the study area is uneven. The primary precipitation period is from June to September, accounting for 70-85% of total annual precipitation. Evaporation also has an uneven distribution spatially and temporally, spring evaporation is the largest, accounting for 46% of the total annual evaporation,while summer, autumn, and winter account for 33%, 16%, and 5% of evaporation, respectively.

The Shijiazhuang area is in the piedmont alluvial plain of the Taihang Mountains, part of the massive and multi-layer complex Quaternary aquifer system in Hebei Plain. The minerals of sediments mainly include calcite, dolomite, silicate, and a small amount of gypsum. The lithology of Quaternary sediments are composed of sub-clay, sandy loam, and different grain sizes of pebbles, gravels and sand layers, with a complex stratigraphic structure (Fig. 2). According to the conditions of groundwater occurrence and pore characteristics of the aquifer medium, the groundwater is divided into three aquifer groups: pore water in loose rock, karst water in carbonate rock, and bedrock fissure water. The study area mainly belongs to loose stratum pore water group. The main recharge form is precipitation infiltration. Controlled by topography and geomorphology, the overall groundwater flow direction is from northwest to southeast,with good runoff condition. Due to the large amount of industrial, agricultural, and domestic water consumption, artificial extraction has become the main form of groundwater discharge. In recent years, with the acceleration of urbanization, persistent groundwater over-exploitation has resulted in a decline in the regional groundwater table (Fig. 3), and large depression cones have formed locally. As a result, it has become a hidden hazard to economic and social development in the area.

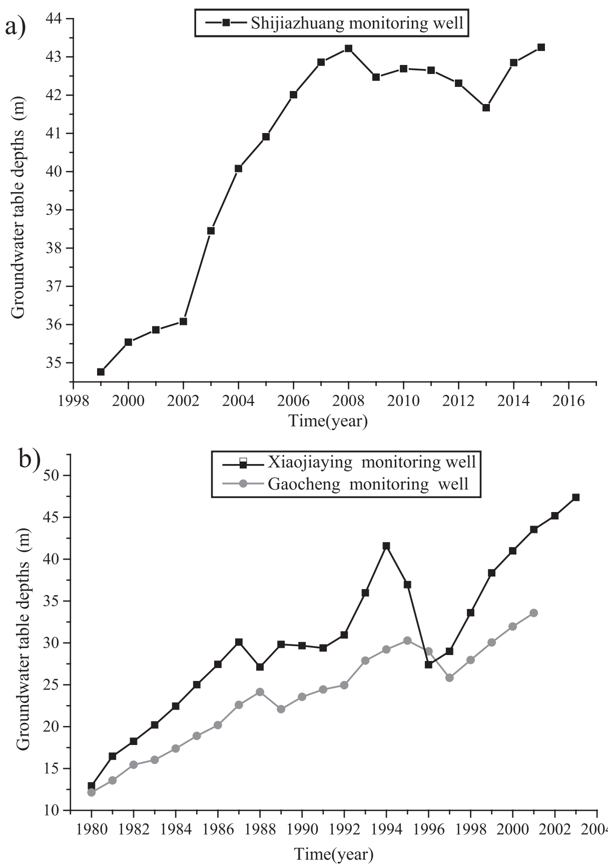

Fig. 3. Temporal evolution of groundwater table depths for Shijiazhuang, Xiaojiaying and Gaocheng monitoring wells.

Social-Economic and Groundwater Quality Data

The social-economic development data for Shijiazhuang from 1986 to 2014 was mainly collected from the Hebei Statistical Yearbook (1986-2014), Hebei Rural Statistical Yearbook (1986-2014), and Shijiazhuang Statistical Yearbook (1986-2014). The datainclude: gross domestic product (GDP); primary industry, i.e., farming, forestry, animal husbandry, and aquaculture GDP (PIGDP); secondary industry or processing industry GDP (SIGDP); tertiary industry or service industry GDP (TIGDP); cultivated land area (CL); permanent population (PP); population density (PD); urbanization;and amount of pure chemical fertilizer dosage (APCFD).

We obtained groundwater monitoring data (1986-2014) from 8 long-term monitoring stations (Fig. 1), which collected from the groundwater quality monitoring department for Shijiazhuang. The data is composed of pH, K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, F^-, salinity, and hardness.

Statistical Analysis

To explore the inherent relationship between social-economic development and groundwater quality, we applied Pearson correlation coefficient analysis and principal component analysis (PCA). The former was used to determine the relationship between groundwater quality parameters and social-economic development, while the latter was used to investigate the impact of various social-economic development indicators on groundwater quality indexes. All statistical analyses were performed using SPSS.21.

Results

Urbanization

China has experienced rapid urbanization and industrialization since the reform and opening up in the late 1970s [18]. In Shijiazhuang, a medium-sized Chinese city, the urbanization process has lagged behind large cities, such as Beijing and Shanghai.

As shown in Fig. 4a), Shijiazhuang's PP, PD, and urbanization ratio show an exponential increase from 1986 to 2014, reaching 1.1×10^7 residents, 695 Km^2 in the capital, and 56.17%, respectively. With these increases, Shijiazhuang's GDP have also exponentially increased from 1986 to 2014; the GDP is nearly 65 times larger than 29 years ago, while per capita GDP rose from 2584 Yuan in 1986 to 48702 Yuan in 2014, with an annual increase of 11% (Fig. 4b). Shijiazhuang is one of the largest pharmaceutical industrial bases and important textile bases in China, and the economic growth is mainly driven by secondary industrial GDP. Recently, as residents have improved their quality of life and awareness of environmental protection, some large factories that caused serious pollution were removed or prohibited, which has changed the industrial structure of Shijiazhuang. The proportion of secondary industrial and primary industrial GDP has decreased, and the proportion of tertiary GDP has increased significantly (Fig. 4c).

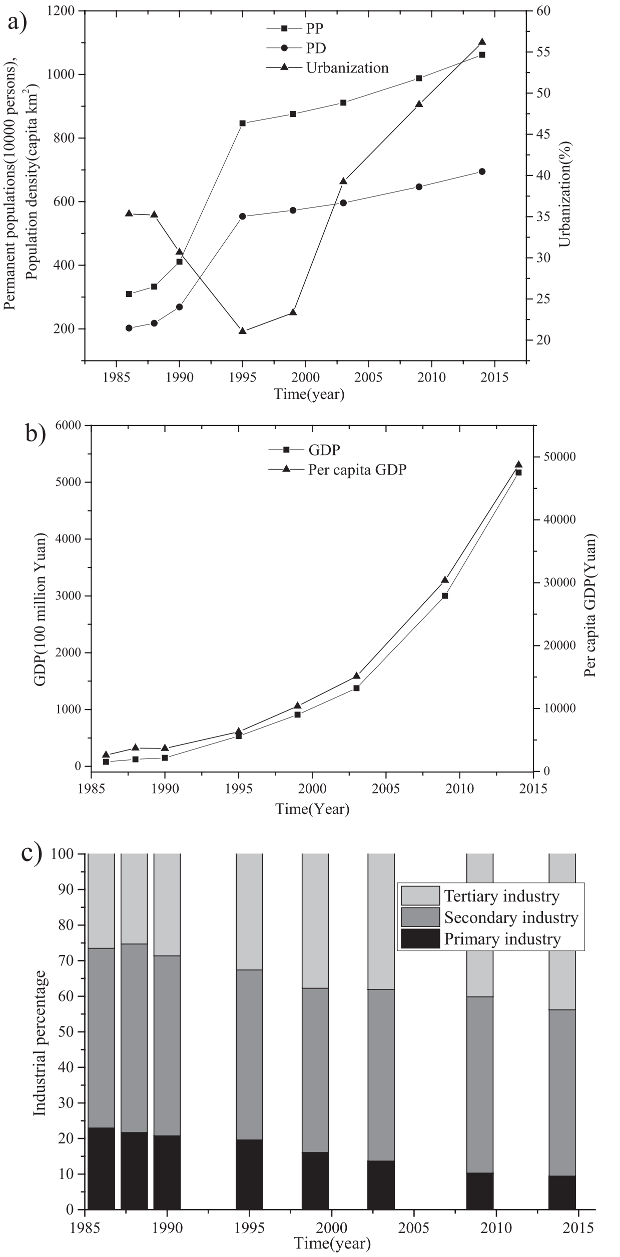

Fig. 4. a) Shijiazhuang's PP and PD growth and urbanization process; b) Shijiazhuang's GDP and per capita GDP growth; c) Shijiazhuang's industrial structure.

Dynamic Variation in Groundwater Level

In the Shijiazhuang area, groundwater is the main water supply source for industry, agriculture, and domestic water. Precipitation infiltration is the main recharge mode, and the main mode of consumption is artificial exploitation. In recent years, with accelerating urbanization and industrialization, groundwater exploitation intensity has been increasing, resulting in an annual decrease in groundwater level (Fig. 3). According to groundwater table monitoring dataover many years, the groundwater table in the area has been continuously declining in a staircase, primarily due to over-exploitation of groundwater. As shown in Fig. 3a), the dynamic changes in groundwater level in the main Shijiazhuang urban area are mainly affected by the formation and development of groundwater depression cones. Since it was formed in 1965, the groundwater level has fluctuated, but generally declined with the increase in urban mining. According to historical data, between 1972 and 2000, the groundwater level depth has changed from 13.96 m to 35.54 m, an average annual rate of decrease of 1.04 m/a. Since 2005, the groundwater level has decreased slowly and it has been fluctuating between 42 and 43 m due to the government limiting the amount of groundwater mining. As shown in Fig. 3b), the groundwater level trends in the Shijiazhuang urban area and suburban counties (e.g., Gaocheng County) are almost equivalent, both showing a downward tendency. The dynamic changes in the groundwater table are mainly affected by the change in rainfall intensity, and continuous industrial exploitation; declining groundwater levels are higher in urban regions than in suburban areas.

Temporal Evolution in Groundwater Hydrochemistry

The formation of hydrochemical components in groundwater is influenced by the long-term geological history and seepage migration process, which include the type and characteristics of rock along the route, and some physical and chemical interactions in the groundwater system. Prior to the 1950s, groundwater exploitation in Shijiazhuang was relatively small with good groundwater quality. The groundwater chemical type was HCO_3-Ca (Mg) (according to Shijiazhuang's report for hydrogeological investigation of water-supply in 1959). However, as the groundwater table has declined, the groundwater environment and hydrochemistry has undergone significant changes. Based on our survey data, the groundwater hydrochemical type in Shijiazhuang has changed significantly. In 1986, there was a transformation from HCO_3-Ca(Mg)-type to HCO_3.SO_4-Ca (Mg), five of the seven conventional monitoring wells were HCO_3.SO_4-Ca (Mg) water) (Fig. 5); then, for 1990-1995, the hydrochemical types of groundwater remained dominated by HCO_3.SO_4-Ca (Mg)-type water, while the hydrochemical environment further deteriorated. One of eight conventional monitoring wells was HCO_3.Cl-Ca (Mg) type water. For 1995-2009, the HCO_3.SO_4-Ca (Mg) type was still the primary groundwater hydrochemical type in the area. However, the proportion of SO_4-type water gradually increased. Notably, there were eight wells with SO_4.HCO_3-Ca (Mg)-type water of the 10 conventional monitoring wells in 2009. For 2009-2014, the groundwater hydrochemical types were more complex. SO_4-type water was found in six of eight conventional wells, Cl-type water was observed in two monitoring wells, and Na-type water was observed in two monitoring wells. With the acceleration urbanization and industrialization, the groundwater environment changes significantly; the groundwater hydrochemical types become more variable and complex. Continued urban development will cause changes in the groundwater chemistry and quality, which may restrict the socio-economic development and urbanization process in turn.

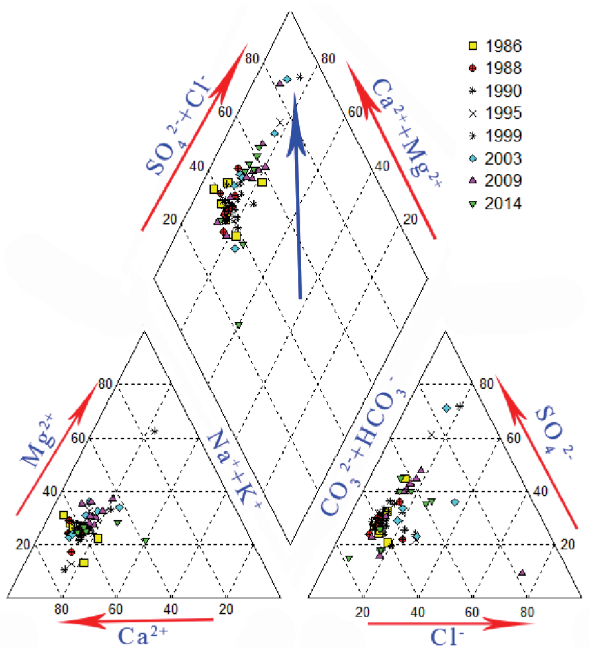

Fig. 5. Piper plot showing the temporal evolution of chemical compositions for groundwater in Shijiazhuang.

Temporal Evolution in Groundwater Quality

Groundwater quality evolution is closely linked to the development of cities in the area. Before 1950, Shijiazhuang was a small city with few industries (including textiles, transportation, and coal). There was a small urban population, little demand on water resources, low groundwater exploitation intensity, and good groundwater quality. Based on historical records, the groundwater salinity was less than 0.5 g/L before 1950. In 1959, while the concentration of NO_3^- was only 2.35 mg/L and pH was 7.69; these values represent the background of the groundwater quality in this area. From the early 1970s to early 1980s, sulfate concentrations increased from 52.6 mg/L to 76.6 mg/L, andNO_3^- concentration increased, although it was generally <20 mg/L. After 1985, with accelerating urbanization in Shijiazhuang, the concentrations of all water quality indicators generally showed an upward trend. As shown in Fig. 6a), the temporal trend in pH is wavy and stable, and all samples met the grade III national quality standard range 6.5-8.5 for groundwater in China [19]. Fig. 6(b, c, d) show that K^+, Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and Cl^- have gradual upward trends in a wave form, while HCO_3^- has a decreasing and then increasing trend. NO_3^-, salinity and hardness, greatly affected by urbanization, show a linear upward trend; furthermore, NO_3^- in 2014 (89.52 mg/L) and hardness in 2003 (458.37 mg/L) exceeded the grade III national quality standard range (88.6 mg/L and 450 mg/L) for groundwater in China (GB/T 14848-2017).

Discussion

Although urbanization has raised living standards, it has also led to over-exploitation of resources, massive emission of pollutants, and consequent environmental degradation. Historically, scholars have primarily focused on air and surface water pollution, and given little attention to groundwater pollution caused by rapid urbanization. However, in recent years, China's groundwater pollution has attracted some attention [13, 15, 20]. Shijiazhuang, as the capital city of Hebei Province, witnessed accelerating urbanization and industrialization and a rapidly increasing population, resulting in an increase in consumption of water resources daily. Unfortunately, there are relatively few available surface water resources in Shijiazhuang, which leads to over-exploitation of groundwater resources. This has resulted in the formation of a regional groundwater depression cone, the groundwater funnel area reached 452.5 km^2 in 2012, and the groundwater quality has also deteriorated significantly [16, 21]. Groundwater problems caused by rapid urbanization mainly include the changes in the groundwater environment and the deterioration of groundwater quality, which resulted from the over-exploitation of groundwater.

Impact of Urbanization on Groundwater Environment

As urbanization accelerates, the demand for water resources increases, especially in the areas where surface water is scarce, which leads to intense groundwater exploitation and continuous declines in the groundwater table, as documented. This results in the formation of regional depression cones and a change in the original balance of groundwater hydrodynamic field. As a result, groundwater flow paths, the thickness of the aeration zone increases, the recharge distance lengthens, and there is an increased the reaction time between the recharge water source and ions in the soil, and enhanced water-rock interactions cause a series of physicochemical reactions. The new physical flow paths facilitate the dissolution of carbonate minerals (e.g., calcite, limestone and dolomite) [21], and the concentrations of HCO_3, Ca^{2+}, and Mg^{2+} increase. Therefore, groundwater hardness increases, which in turn leads to changes in groundwater hydrochemical types. We found that the groundwater hydrochemistry type in Shijiazhuang area has changed from a dominantly HCO_3-Ca (Mg) type to $HCO_3.SO_4$-Ca (Mg) type.

Further more, due to the thickening of the aeration zone, the original saturated water zone turns becomes aerated, and the aeration status of the soil changes. As a result, the groundwater environment is transformed from a reducing to an oxidizing environment, which facilitates the formation of certain pollutants. For example, the transformation of ammonia to nitrate, as shown in the following equations:

$$2NH_4^+ + 3O_2 \xrightarrow{\text{Nitrite bacteria}} 2NO_2^- + 2H_2O + 4H^+ + 158 \text{ kilocalories} \quad (1)$$

$$2NO_2^- + O_2 \xrightarrow{\text{Nitrifying bacteria}} 2NO_3^- + 40 \text{ kilocalories} \quad (2)$$

In addition, as the aeration zone thickens, the recharge distance increases, resulting in an increased evaporation of soil moisture, slowing the replenishment cycle of groundwater resources and reducing the recharge rate, resulting in a faster decline in groundwater levels and further deterioration of the groundwater environment.

Finally, with rapid urbanization, the area and scale of cities in China have continuously expanded, accompanied by an increasing proportion of impervious surface area. The impervious underlying surface changes the original hydrological cycle and reduces groundwater recharge, which also accelerates the decline

Table 1. Pearson correlation coefficients between water quality parameters.

Parameter	pH	K^++Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	NO_3^-	Salinity	Hardness
pH	1.000	-0.239	-0.088	0.221	0.475	0.119	-0.844**	-0.125	-0.105	0.028
K^++Na^+		1.000	0.861**	0.800*	0.704	0.717*	-0.058	0.922**	0.916**	0.889**
Ca^{2+}			1.000	0.769*	0.646	0.931**	-0.163	0.965**	0.974**	0.969**
Mg^{2+}				1.000	0.939**	0.639	-0.263	0.869**	0.871**	0.903**
Cl^-					1.000	0.594	-0.520	0.732*	0.735*	0.799*
SO_4^{2-}						1.000	-0.440	0.821*	0.844**	0.874**
HCO_3^-							1.000	-0.067	-0.091	-0.214
NO_3^-								1.000	0.997**	0.983**
Salinity									1.000	0.990**
Hardness										1.000

Note: *P<0.05; **P<0.01

in groundwater levels and a deteriorated groundwater environment.

The Impact of Urbanization on Groundwater Quality

The effect mechanism of urbanization on groundwater quality is mainly groundwater extraction and human activities, which changes the groundwater dynamic condition and the change of groundwater hydrochemistry field. Urbanization and industrialization consume large amounts of resources, and increase the total amount of pollutants, such as industrial wastewater, domestic sewage, solid waste, pesticides, and fertilizers. Table 2 shows that, except for pH and HCO_3, other water-quality parameters exhibit a significant or highly significant positive correlation with GDP, resident population, and population density. Previous research has also found that the concentration of NO_3^- significantly correlates with GDP, PP, and PD [18, 20]. In addition, the urbanization level also shows a significant positive correlation with Cl^-, Mg^{2+}, NO_3^-, salinity, and hardness. In recent years, the GDP and population in Shijiazhuang have grown rapidly, accompanied by a significant increase into tal amount of industrial sewage, domestic sewage, and solid waste, whiles up porting facilities for sewage and solid waste treatment remain poor, domestic and industrial sewage effluent have not met standards, and solid waste disposal is challenging. Furthermore, in order to increase production, farmers use fertilizers, manure, and even sewage irrigation, which will have a serious impact on groundwater quality in the area. Cl^-, SO_4^{2-}, and NO_3^- are important indicators that reflect the impact of human activities on groundwater quality [22]. As shown in Fig. 6, with rapid urbanization, Cl^-, SO_4^{2-}, and NO_3^- have gradually increased in a wave-like trend, indicating the significant influence of human activity.

The strong exploitation of groundwater is the incentive for the deterioration of groundwater quality in the Shijiazhuang area. As shown in Fig. 6 and Table 2, the mineralization and total hardness of groundwater increases annually with accelerating urbanization. This is mainly due to groundwater over-exploitation, which leads to declining groundwater levels and the alternating aquifer redox conditions. As a result, the oxidative decomposition of organic matter accumulated in the stratum is enhanced. When infiltrating water passes through the soil containing large amounts of calcium and magnesium carbonate, they are partially dissolved and the pH value decreases [21]. Fig. 6(a-c) shows that the concentration of Ca and Mg in groundwater gradually increases while pH has declined. Concurrently, as shown in Table 1, groundwater pH has a significant negative correlation with HCO_3^-,which indicates that total hardness and mineralization have a common source of contamination with Cl^-, SO_4^{2-} and NO_3^-, and are also affected by human activity. The increase in total hardness has been influenced by changes in environmental geological conditions, i.e., over-exploitation of groundwater, and anthropogenic environmental pollution.

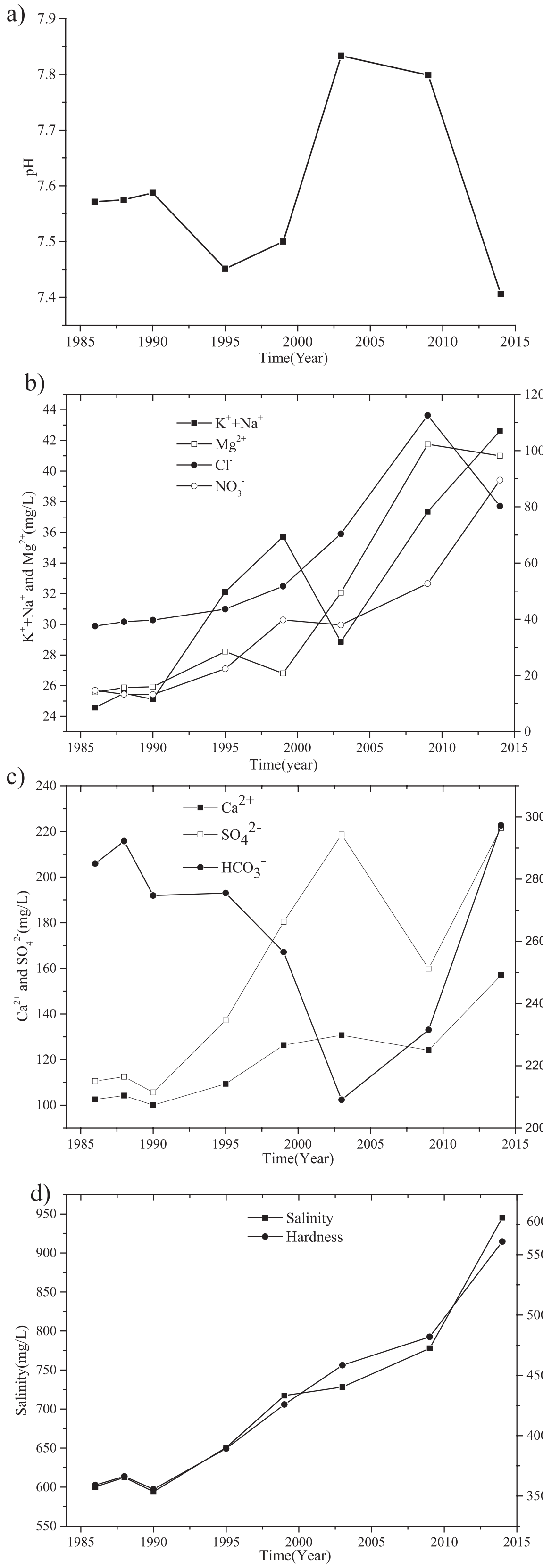

Fig. 6. Temporal evolution of groundwater quality for Shijiazhuang region.

Table 2. Pearson correlation coefficients between the water quality parameters and social and economic indexes.

Parameters	PIGDP (100 million yuan)	SIGDP (100 million yuan)	TIGDP (100 million yuan)	GDP (100 million yuan)	CLA (100 km^2)	PP (10000 persons)	Urbanization (%)	PD (capita km^{-2})	APCFD (ton)
pH	-0.050	-0.055	-0.113	-0.080	0.058	0.067	0.232	0.067	0.128
K^++Na^+	0.915**	0.878**	0.871**	0.879**	0.478	0.881**	0.490	0.881**	0.804*
Ca^{2+}	0.937**	0.899**	0.904**	0.906**	0.414	0.829*	0.650	0.829*	0.759*
Mg^{2+}	0.927**	0.938**	0.911**	0.927**	0.220	0.761*	0.832*	0.761*	0.666
Cl^-	0.797*	0.794*	0.747*	0.775*	0.236	0.744*	0.720*	0.744*	0.692
SO_4^{2-}	0.797*	0.723*	0.718*	0.728*	0.426	0.852**	0.477	.852**	0.819*
HCO_3^-	-0.117	-0.042	0.017	-0.023	-0.407	-0.450	-0.035	-0.450	-0.542
NO_3^-	0.988**	0.975**	0.977**	.978**	0.370	0.813*	0.735*	0.813*	0.732*
Salinity	0.989**	0.972**	0.973**	.975**	0.406	0.828*	0.733*	0.828*	0.740*
Hardness	0.988**	0.966**	0.959**	.966**	0.383	0.855**	0.755*	0.855**	0.772*

Driving Mechanism of Groundwater Quality Deterioration

Groundwater quality is influenced by many factors. In this study, we used PCA to identify the main factors causing groundwater quality deterioration. As shown in Table 3, PCA reduces the original 19 variables into three key independent factors. Based on eigenvalues >1, PCA generated three principal components (PCs) accounting for 95.86% of the total variance.

As shown in Table 3, PC1 accounted for 74.58% of the total variance and had strong positive loadings for K^+, Na^+, NO_3^-, salinity, PD, and PP, and moderately positive loadings for Mg^{2+}, Cl^-, hardness, GDP, PIGDP, SIGDP, TIGDP, and APCFD. PD and PP are indexes that reflect population growth, and are strongly correlated with NO_3, salinity, K^+, and Na^+. Zhang and colleagues [20] found that the concentrations of groundwater NO_3^- in a rapidly urbanized region was significantly correlated with the PP and PD. These increases in a city's PP and PD cause an increase in the amount of domestic wastewater and solid waste, which results in these pollution sources discharging into the aqueous environment and inevitably infiltrate groundwater. Therefore,there is a direct link to deteriorating groundwater quality. Thus, PC1 can be identified as population growth factor as a driving force of groundwater quality deterioration.

PC2 accounted for 14.43% of the total variance and had strong positive loadings for urbanization, pH, Mg^{2+}, Cl^-, GDP, PIGDP, SIGDP, TIGDP, and moderately negative loadings for HCO_3^-. Urbanization, GDP, PIGDP, SIGDP, and TIGDP are indexes that reflect social and economic development. This development consumes resources and produces large amounts of pollutants, such as industrial wastewater, solid waste, and animal manure. If mishandled, these pollutants will inevitably

Table 3. Driving mechanism of groundwater quality deterioration under a rapid urbanization process.

Parameters	Principal components		
	PC1	PC2	PC3
K^++Na^+	0.943	0.074	0.226
NO_3^-	0.714	0.454	0.504
PD	0.685	0.165	0.551
PP	0.685	0.165	0.551
Salinity	0.678	0.442	0.565
APCFD	0.592	0.152	0.559
Urbanization	0.053	0.970	0.080
pH	-0.072	0.901	0.427
Mg^{2+}	0.560	0.796	0.122
Cl^-	0.573	0.784	0.212
SIGDP	0.543	0.720	0.225
TIGDP	0.545	0.718	0.230
GDP	0.549	0.708	0.243
PIGDP	0.584	0.682	0.384
SO_4^{2-}	0.235	0.160	0.941
Ca^{2+}	0.468	0.242	0.835
HCO_3^-	-0.153	-0.590	-0.752
Hardness	0.576	0.540	0.592
CLA	0.227	-0.061	0.229
Eigenvalue	14.17	2.74	1.30
% total variane	74.58	14.43	6.85
Cumulative %	74.58	89.01	95.85

infiltrate into groundwater and worsen groundwater quality. Thus, PC2 can be identified as social and economic development factor as a driving force for groundwater quality deterioration.

PC3 accounted for 6.85% of the total variance and had strong positive loadings for SO_4^{2-}, Ca^{2+}, and hardness, and had strong negative loadings for HCO_3^-. These indexes are mainly related to water-rock interactions [21, 23]. In Shijiazhuang, rapid urbanization and groundwater exploitation has resulted in a groundwater depression cone and continually increasingvadose zone thickness. These changes to the environment have impacted the hydrodynamic field and hydrogeochemical environment and led to enhanced water-rock interactions. Thus, PC3 can be identified as the over-exploitation of groundwater as a driving force for groundwater quality deterioration.

Conclusions

The present study uses Shijiazhuang as a representative city in China in order to explore the effects of rapid urbanization on groundwater environment and quality based on groundwater monitoring data (1986-2014) from long-term monitoring stations and social-economic development data (1986-2014) from the Hebei Statistical Yearbook. The following conclusions were drawn.

With accelerating urbanization, the groundwater table has continuously declined in step form, from 13.96 to 43.25 m between 1972 and 2015, and the average rate of decrease has been higher in urban than suburban areas. The groundwater environment has undergone significant changes caused by the intense exploitation of groundwater, with a corresponding change in groundwater hydrochemistry from HCO_3-Ca (Mg) to HCO_3.SO_4-Ca (Mg) type, and an increase in variability and complexity. The change in oxidation-reduction environment, thickening vadose zone, and increasing proportion of impervious surface area are important factors causing groundwater environment changes.

Groundwater quality has also deteriorated significantly;the concentration of NO_3^- in 2014 and hardness in 2003 exceeded grade III of the national quality standard range (88.6 mg/L and 450 mg/L, respectively) for groundwater in China (GB/T 14848-2017). The concentrations of Cl^-, SO_4^{2-}, and NO_3^- have been significantly affected by human activity, and have increased gradually in a wave-liket rend. The concentrations of Cl^-, Mg^{2+}, NO_3^-, salinity, and hardness were significantly positively correlated with GDP, PP, and PD.

Based on PCA analysis, the driving factors causing groundwater quality deterioration are population growth factor, social and economic development factor and over-exploitation of groundwater. Therefore, the state and the administration should balance the protection of groundwater environment with the pursuit of rapid socioeconomic development.

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Conflict of Interest

The authors declare no conflict of interest.

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