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Research Article

Evaluating Spatiotemporal Variation of Groundwater Depth/Level in Beijing Plain, a Groundwater-Fed Area from 2001 to 2010

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Groundwater has always been a valuable resource in Beijing, facing a great decline of groundwater level during the past decades. However, few previous researches have revealed the spatial variation of groundwater level within Beijing Plain. In this study, spatiotemporal variation of groundwater level from 2001 to 2010 in Beijing Plain has been investigated. Factor analysis has been conducted to identify the primary influencing factor. Results showed that the groundwater level decreased by 8.41 m from 2001 to 2010, with a linear decreasing rate of 0.954 m per year averagely. Significant spatial variation characteristics have been detected. The north area suffered more groundwater depletion than the south part in general. The lowest groundwater level has been identified downstream Miyun Reservoir, central part of the Plain. Nevertheless, the most of the south part witnessed a slight revival between 2001 and 2010. This may be due to the differences of socioeconomic circumstances in the Plain. Three influencing factors, that is, "demand factor," "supply factor," and "loss factor," have been identified in the water balance model. Eigenvalues of these factors are 3.563, 2.910, and 1.632, respectively, indicating that these factors influenced the groundwater system to various extents, with the demand factor being the primary one.

1. Introduction

Beijing has been known for its great dependence on groundwater. Interannual variation of groundwater depth/level is of great significance to water resources management in Beijing. Although high temporal resolution monitoring networks have been established in many areas, it is not easy to obtain these data in many parts of China. Moreover, the interannual variation of groundwater depth could provide long-term information of the territorial water crisis for urban planning compared to seasonal and monthly data [1]. For the practical reason, most cities or basins record yearly data of groundwater depth/level in China, which is necessary for interannual analysis. Additionally, interannual fluctuation of groundwater depth/level is adaptable to reflect the large temporal scale dry/wet conditions [1–3].

A sharp decline has been witnessed in the groundwater level in Beijing Plain in the early 21st century. This megacity relies upon groundwater resources heavily in the past. Groundwater supply is made up of more than 70% of the total water supply at the beginning of 21st century. According to the *Beijing Water Resources Bulletin 2013*, Beijing has a water supply of 3.64 billion m^3, which is 50 million m^3 larger than that of 2012. The water supply derives from surface water of 0.48 billion m^3 (13%), groundwater of 2.01 billion m^3 (55%), reclaimed water of 0.8 billion m^3 (22%), and water from the *South-to-North Water Diversion* of 0.35 billion m^3 (10%). To release the depletion of traditional water resources, Beijing has developed reclaimed water and transferring water in the last decade. Since the *South-to-North Water Diversion Project (Middle Route)* was completed in 2014, Beijing gained gradually added transferred water (1.05 billion m^3 per year) from the Yangtze River Basin. It seemed likely that the water scarcity in Beijing would be alleviated to some extent; however, groundwater resources still consisted of more than 50% of the total amount in 2013 [4].

Though it has been well understood that the groundwater experienced a severe depletion in the past years, the spatial variation of groundwater remains still insufficiently studied, which is of great importance in groundwater management. For instance, the Beijing Plain, one of the largest urban areas in the world, showed great inner spatial difference in urban development. This indicates that the Plain cannot be treated as a whole. Wang et al. [5] and Song et al. [6] divided Beijing into four and six subunits, respectively, considering the effects of topography and urban span. Rapid urbanization is enlarging the gap between metropolitan areas and suburban areas. Zheng et al. [7] have confirmed that the groundwater renewability varied across the Beijing Plain. Therefore, the spatial variation of groundwater level is a necessity in Beijing Plain as well as other urban areas globally.

Given that a number of researches of spatiotemporal variation of groundwater level in Beijing Plain have been initiated [8–10], it is of great importance to seek the possible causes to the variation. Recent researches showed that the groundwater depletion could be attributed to decreasing precipitation, increasing water demand, water extravagancy, poor utility ratio, and other unpredicted problems [11–15]. Numerical models have been proven to be an effective way to investigate the relationship between groundwater level and environmental-social factors [16, 17]. For example, Terrie et al. have explored the long-term balance of precipitation and groundwater exchange in the peninsular lake district. Results showed that net groundwater exchange with the lake was positive on average but too small to balance the net precipitation deficit, while some recent studies illustrated that rainfall is influencing the groundwater depths in quick and slow pattern [18, 19]. Evapotranspiration was also linked to groundwater at high water table region [20]. However, when the groundwater depth is over a threshold, this linkage is no longer strong enough to influence the water table [21]. Then, the groundwater evapotranspiration (*ETg*) is eliminated from the actual evapotranspiration (*ETa*).

Studies also indicated that net groundwater imbalance could be widened by groundwater pumping and surface water withdrawals [22]. For instance, Eshtawi et al. (2015) have studied the potential impacts of urban expansion, related to water supply and groundwater recharge, on groundwater depth via the combination of surface water model and MODFLOW-USG [15]. Local water management practices could significantly alter the groundwater quantity in the territorial system [23]. It has been reported that total groundwater consumption accounted for 43% of the total irrigation water use globally [13]. Increasing water supply demand has been reported resulting from rapid increase in population, urbanization, and industrialization [24]. This trend would bring larger stress on local water crisis and groundwater sustainability.

Most previous studies relied on only a few scattered groundwater monitoring stations and did not reveal the spatial difference of groundwater level within the Plain [8]. Consequently, the important role of urban span, which should be discussed by detailed subunits, played in the distribution of groundwater level could not be well analyzed. In this study, an evenly distributed and high-resolution groundwater level database was used to remedy this shortcoming. By dividing the Beijing Plain into three subareas, the spatial characteristics of groundwater variation could be detected, which could benefit future physically based studies.

Even fewer of them have witnessed the driving forces of groundwater level in the perspective of water balance. Previous studies were often data-driven, which made the detection less effective. Therefore, we have proposed a factor analysis method, combined with correlation analysis, based on a regional water balance model, to identify the major factors that contribute to the variation. For the purpose of water resources management and strategy-making, this variable-fair method could be more valuable and cost-effective than pure mathematical models and be applied to other groundwater-fed urban areas.

2. Study Area

Beijing Plain has a geographic location of $115^{\circ}40'–117^{\circ}24'$E and $39^{\circ}26'–40^{\circ}27'$N with a total coverage of 116,512 km^2, located mainly in the center and southeast part of Beijing. The elevations range from 10 to 500 m, with the northwest being relatively high and the southeast being low generally.

Beijing, the capital of China, located in the northwest of North China Plain, is a megacity directly controlled by the central government and also the political and economic center. Within the 16 districts of entire Beijing, 9 districts were covered by the study area in whole or in part [25]. Five natural rivers, Juma river, Yongding river, Beiyun river, Chaobai river, and Linyun river, with 85 reservoirs are located in the Beijing Municipality, while the Miyun reservoir and Guanting reservoir consist of 90.5% of the surface water resources [4].

As one of the largest cities in the world, Beijing is facing severe water shortage problems. This city has an annual average precipitation of 595 mm, which is about 9.9 billion m^3 each year. However, 37.78% of the precipitation transforms to available water resources (3.74 billion m^3) due to 60.6% (6 billion m^3) of the high evapotranspiration. Beijing owns a growing population of 21, 516, 000 in 2014, which generates a huge amount of water demand each year. While more than 50% of water resources derive from groundwater, the continuous declining of groundwater level has become a key constraint factor to the social development. The paradox between increasing water demand and limiting water resources keeps sustainable development of living challenging. Beijing has always kept water scarcity as one of the priorities in China, which deserves cost-effective strategies in dealing with water problems. Beijing is confronted with the fact that water resources per capita were 117 m^3 in 2013, which is 12.5% of China and 3.33% of the world [4].

Table 1: Variables selected from the Beijing Water System.

Number	Variables	Unit	Symbols	Data series
1	Inflow	$10E08\ m^3$	Qin	2001–2010
2	Outflow	$10E08\ m^3$	Qout	2001–2010
3	Surface water resources	$10E08\ m^3$	SWR	2001–2010
4	Groundwater resources	$10E08\ m^3$	GWR	2001–2010
5	Precipitation	$10E08\ m^3$	Pa	2001–2010
6	Agricultural water use	$10E08\ m^3$	AWU	2001–2010
7	Industrial water use	$10E08\ m^3$	IWU	2001–2010
8	Domestic water use	$10E08\ m^3$	DWU	2001–2010
9	Environmental water use	$10E08\ m^3$	EWU	2001–2010
10	Groundwater depth/level	m	GWD	2001–2010

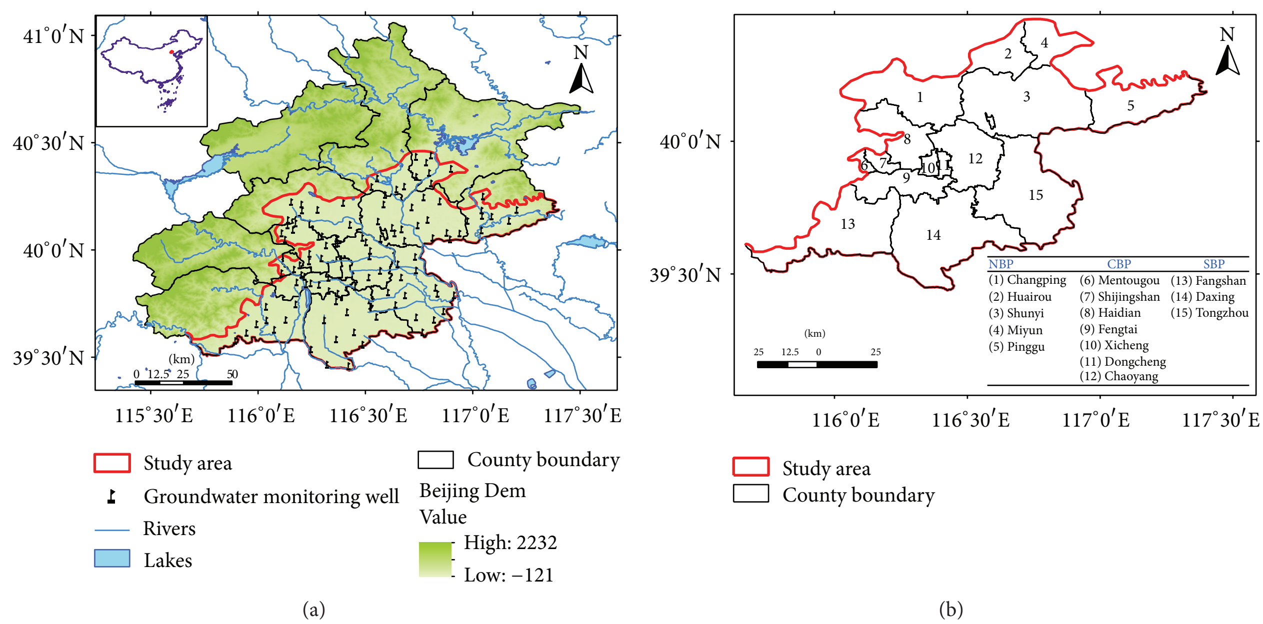

Figure 1: (a) Location of the study area and the 106 groundwater monitoring wells in Beijing Plain. Red solid lines denoted the boundary of study area, namely, Beijing Plain. (b) Subareas division of Beijing Plain.

3. Materials and Methods

3.1. Data Sources. Temporal data of inflow (Qin) and outflow (Qout), surface water and groundwater storage (SWR and GWR), precipitation amount (Pa), and water use by sectors were derived from Beijing Water Bulletin (2001 to 2010) and published references [4]. The basic information of the temporal dataset is shown in Table 1.

Distributed groundwater monitoring data from 2001 to 2010 were collected from the field groundwater monitoring wells. We selected 106 groundwater monitoring sites in Beijing Plain to obtain the spatial characteristics of groundwater depth/level. These monitoring wells were evenly distributed in the study area, which could demonstrate the spatial variation reasonably. Afterwards, Beijing Plain has been divided into three subareas according to the geographical feature: NBP, CBP, and SBP, respectively. These three subareas represented the north, central, and south part of the Plain (Figure 1). The NBP contains Changping, Shunyi, and Pinggu districts, the CBP contains Haidian, Mentougou, Shijingshan, Fengtai, Xicheng, Dongcheng, and Chaoyang districts, and SBP contains Fangshan, Daxing, and Tongzhou districts. Generally, the north and west part are relatively higher than the south and east part. These three subareas differ from each other in terms of social and economic status. The NBP comprises the majority of the irrigated land in Beijing Plain, and the CBP represents the economic and population center, while the SBP is less developed compared with the other two subareas due to its location [26, 27].

3.2. Trend Analysis. The methods of linear regression were used to analyze the temporal trends of the groundwater depth in this study [28]. Linear regression is a parametric method used to obtain the trend of groundwater depth/level variables over time [5, 8]. The linear regression equation can be represented as

$$y = a + bx + \varepsilon. \quad (1)$$

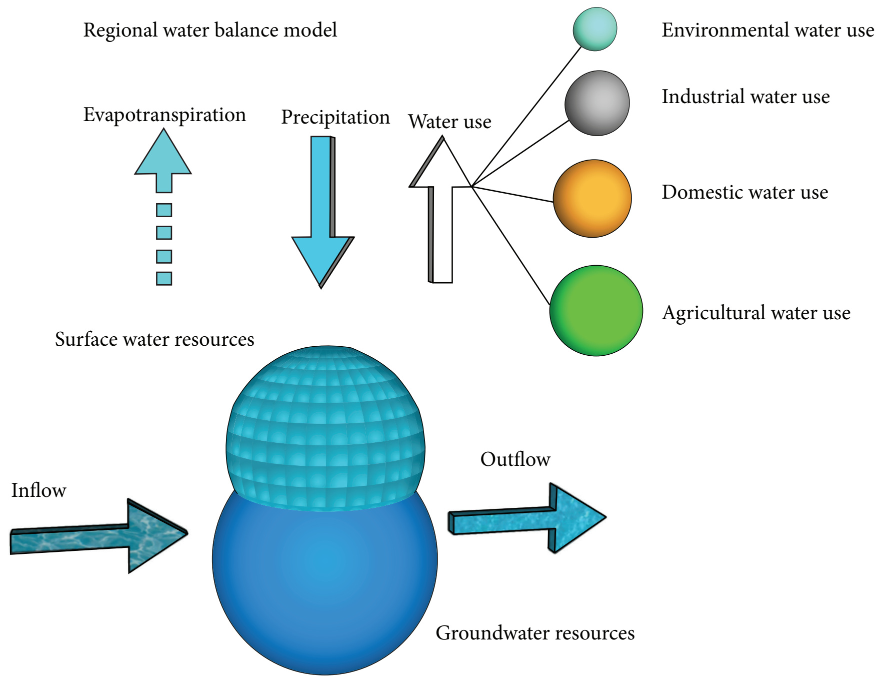

FIGURE 2: Theoretical water balance model of Beijing Water System.

The slope b can be used as an indicator of trend and is calculated as

$$b = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}, \quad (2)$$

where y_i is the groundwater depth/level, x_i is the time, and n is the length of time sequence. Statistically significant b indicates the slope of a linear trend. Additionally, smooth regression lines have been used to demonstrate the long-term trend of the groundwater depth/level [29, 30].

3.3. Mann-Kendall Test. We examined the general trend and the abrupt changing point using Mann-Kendall test for the groundwater level time series [31, 32]. The Mann-Kendall test is widely used for nonlinear trend and turning point test. The indexes of the Mann-Kendall test were calculated as follows:

$$\begin{aligned} \mathrm{UF}_k &= \frac{s_k - E(s_k)}{\sqrt{\mathrm{Var}(s_k)}}, \quad k = 1, 2, \ldots, n, \\ s_k &= \sum_{i=1}^{k} r_i, \quad r_i = \begin{cases} 1 & (x_i > x_j) \\ 0 & (\text{else}), \end{cases} \quad j = 1, 2, \ldots, i, \\ E(s_k) &= \frac{n(n-1)}{4}, \\ \mathrm{Var}(s_k) &= \frac{n(n-1)(2n+5)}{72}. \end{aligned} \quad (3)$$

For a time series $\vec{x} = (x_1, x_2, \ldots, x_n)$, n stands for the length of the time series. UF_k and UB_k are the two statistical indices of the Mann-Kendall test, s_k stands for an accumulative value of r_i, $E(s_k)$ stands for the mean value of s_k, and $\mathrm{Var}(s_k)$ stands for the variance of s_k. Then, invert the time series sequence to form a new one $\bar{x} = (x_n, x_{n-1}, \ldots, x_1)$, and calculate the indexes above once more and UB_k for the new time series $\bar{x} = (x_n, x_{n-1}, \ldots, x_1)$. Apparently, the values of UF_k and UB_k are time series as well. Two critical values were set for significance measurement as $U_{0.05} = \pm 1.96$. Finally, the sequence curve of UF_k, UB_k and two horizontal lines indicating the critical values were drawn in the same plot. A significant increasing or decreasing trend could be detected when the curve of UF_k crosses the $U_{0.05} = \pm 1.96$ line. Additionally, statistical results including Kendall's tau, S and p value (two-tailed) have been calculated to identify the trend [28].

3.4. Spatial Interpolation. Spatial interpolation has been widely used for detecting groundwater level distribution from monitoring sites. There exist many methods including polynomial, nearest-neighbor, Inverse Distance Weighted, and Kriging to detect the changing pattern of groundwater level. The ordinary Kriging method was selected in this study, which contains the highest correlation coefficient calculated from the cross-validation test [5]. It also produced the closest representation of the real values, which was in the form of the lowest difference between the observed and predicted values of known data points [5]. Thus, we used the Kriging to obtain the spatial pattern of groundwater depth/level in the study area.

3.5. Driving Force Detection in the Perspective of Regional Water Balance Model. In this paper, 9 variables were introduced to investigate the driving force and major causes of the groundwater variation, particularly, precipitation, inflow, outflow, water storage, and water uses (Figure 2).

Table 2: Results of Mann-Kendall test of groundwater depth/level.

	Kendall's tau	S	p value (two-tailed)	α
Groundwater depth	1	45	$8.31e-05$	0.05
Groundwater level	−1	−45	$8.30e-05$	0.05

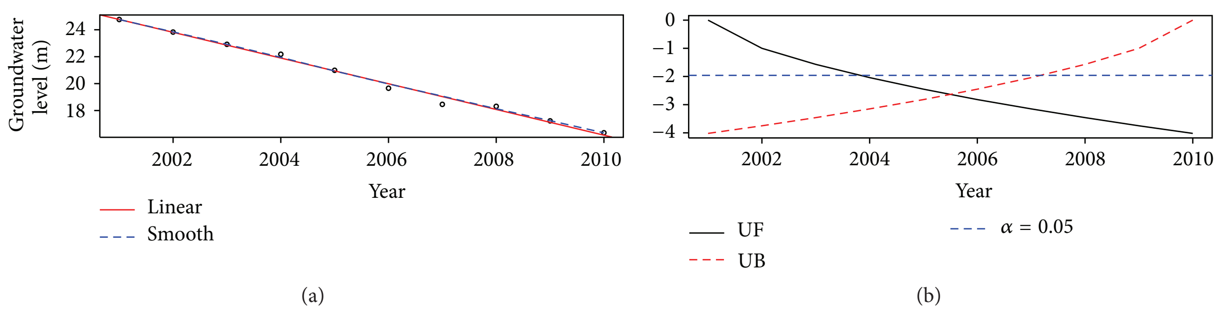

Figure 3: (a) Groundwater level variation during the period 2001 to 2010. (b) Mann-Kendall test results for groundwater level.

These variables were defined as follows. (i) Precipitation amount was averaged to the entire Beijing district based on the observed data of national individual rain gauge stations. (ii) Evapotranspiration was connected with surface water evapotranspiration and groundwater evaporation. Generally, the groundwater evaporation, which often resulted from the upward capillary flux from the underlying aquifer, was rare when the water table was 4 m or more below the ground [33]. It depends on whether the ends of the plant roots are able to reach the water table in this region [34]. Thus, we assumed that the groundwater evaporation was eliminated. (iii) In this study, inflow stands for the overland flow that is produced in the upper reaches of Beijing which flows into the boundary of Beijing and the diverted water from the *South-to-North Water Diversion Project*, while outflow means the drainage which is emitted from the urban drainage system. (iv) Surface water resources and groundwater resources stand for the water storage in Beijing. In this paper, the surface water storage mainly includes the reservoir storage and the stream flow, while the groundwater storage is the sum of crevice water, cavern water, porous confined water, and unconfined water. (v) We categorized water use in four classes: agricultural water use (AWU), industrial water use (IWU), domestic water use (DWU), and environmental water use (EWU).

In the present study, Pearson test was conducted to understand the correlation among these variables. Based on the Pearson test results, factor analysis was implemented to these variables to test whether these variables act in groups and how they work. Maximum Likelihood Estimation (MLE) method was selected as the exact means of factor analysis in this study for dimension reducing analysis [35–37]. Then, major factors were drawn from the factor analysis results, since the variables were picked out from the water balance model, which means the factor analysis is variable-fair. This method could be spread to other groundwater-fed urban areas globally. All the statistical work was conducted by using R programming.

4. Results

4.1. Temporal Analysis of Groundwater Depth/Level in Beijing Plain. Though the groundwater level has been reported to drop for 14.17 m from 1986 to 2013 [4], the mean annual groundwater depth from 2001 to 2010 varies from 17.34 m to 24.94 m with a monotone enlarging trend during the period. The mean annual groundwater level also showed the same variation, which slid from 24.76 m to 16.35 m in Beijing Plain. The linear regression results indicated that the groundwater level experienced a significant falling during the period with a linear variation of −0.954 m each year averagely.

Similar conclusion was drawn from the Mann-Kendall test results of both groundwater depth and groundwater level. There is a clearly declining trend in groundwater level, as Kendall's tau equals −1 with the p value being less than 0.05 (Table 2). The trend is also shown by the black (UF) and red (UB) lines, respectively, and the horizontal dashed lines correspond to the confidence limits at the significance level of $\alpha = 0.05$. Figure 3 shows that a statistically significant trend of decreasing groundwater level which is indicated as the black line crosses over the dashed line since 2004.

4.2. Spatial Characteristics of Groundwater Level in Beijing Plain. Groundwater depth/level records were collected from 106 wells over the period of 2001 to 2010. The data were used to analyze the interannual spatial variations in groundwater conditions (Figure 4). Generally, the north part of Beijing Plain showed a larger groundwater depth than the south part. In 2001 and 2005 (Figures 4(a) and 4(b)), the deepest groundwater depth is spotted in the northeast of the Plain, including partial NBP and CBP, while the largest value moved to the northeast part of the Plain in 2010. It could be deduced that the groundwater depletion was getting worse in the NBP in the period.

In terms of groundwater level, it showed precipitous decreasing gradient from northwest to southeast. While the

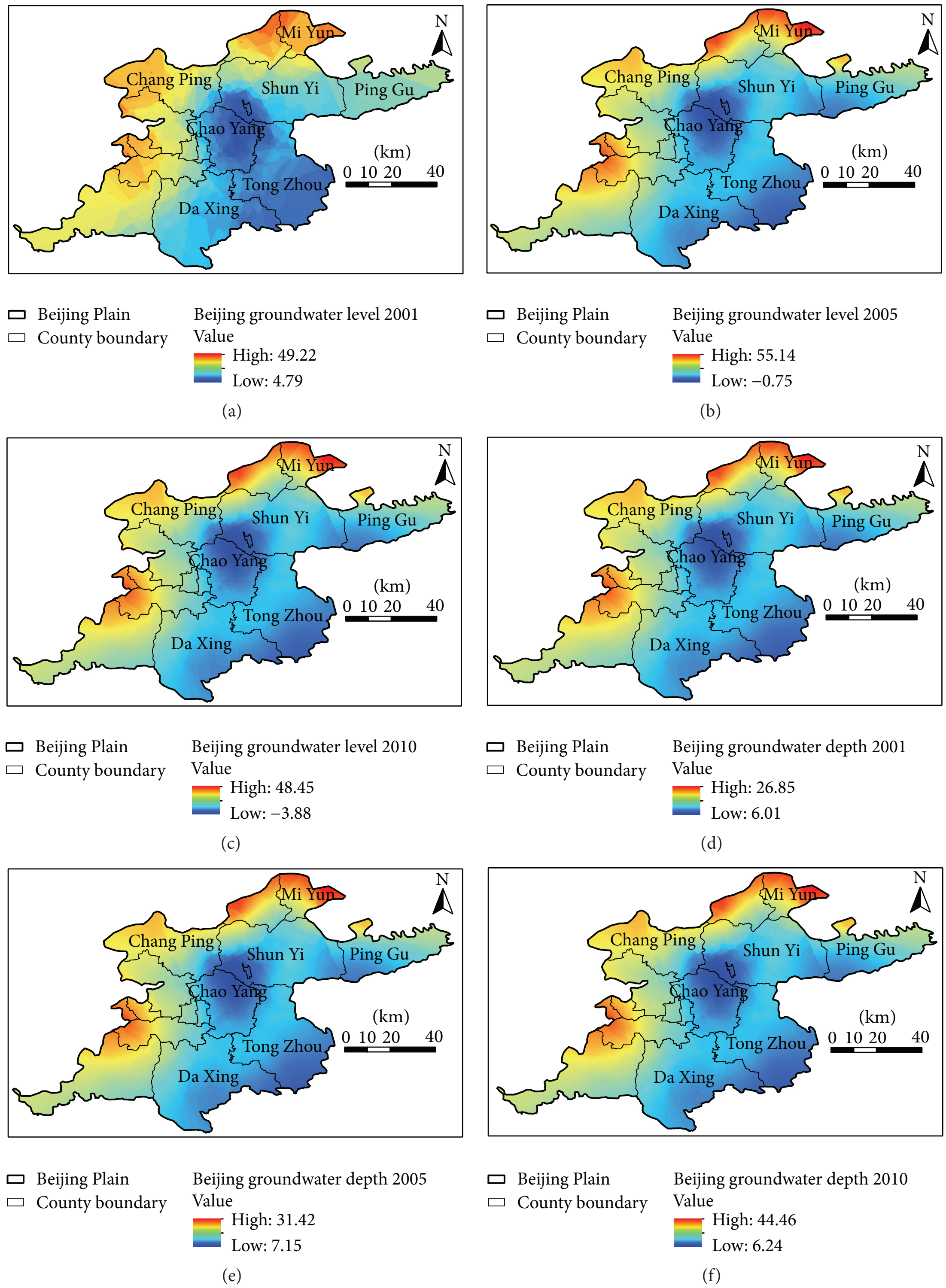

FIGURE 4: Distribution of groundwater depth/level (m) in Beijing Plain: (a) groundwater depth in 2001, (b) groundwater depth in 2005, (c) groundwater depth in 2010, (d) groundwater level in 2001, (e) groundwater level in 2005, and (f) groundwater level in 2010.

elevation of the Beijing Plain declines from the northwest to southeast gradually (Figure 1), it should be noted that the center of the study area (the CBP area) had the lowest groundwater level in 2001, 2005. Similar phenomenon could be detected from Figure 4(f) that the NBP got lower groundwater level in 2010 than the previous years. This difference between the variation of the geomorphological characteristics of Beijing Plain and that of the groundwater level

Table 3: Variation of groundwater level at monitoring station.

Threshold	Difference level	Number of stations	Percentage
<0	L_0	16	15.24%
0~5	L_1	31	29.52%
5~10	L_2	18	17.14%
10~15	L_3	20	19.05%
15~20	L_4	5	4.76%
20~25	L_5	6	5.71%
25~30	L_6	9	8.57%

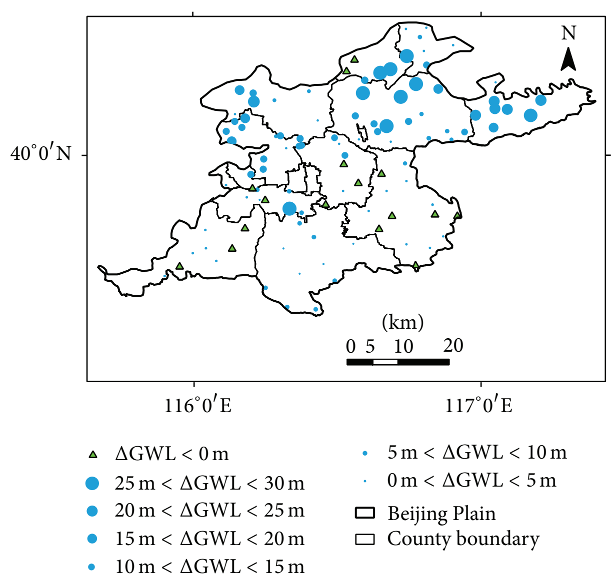

Figure 5: Bubble plot of groundwater level decreasing in Beijing Plain between 2001 and 2010.

indicates that local impacts severely influenced the groundwater level.

The groundwater depth/level data were further divided into seven categories: L_0~L_6 (Table 3). The monitoring sites where the groundwater level increased from 2001 to 2010 were defined as L_0. Those sites where the groundwater level was decreasing from 2001 to 2010 were classified into L_1~L_6 with an interval of 5 m.

Spatial variation showed that the groundwater level has different changing pattern in the research period. Among the monitoring data, 29.52% of them changed in 5 m, which accounted for most of the stations. Those 17.14% of the sites witnessed a groundwater level decreasing in the threshold of 5 to 10 m and 19.05% of them in the threshold of 10 to 15 m. Those points in which the groundwater level decreased at more than 15 meters comprised only 19.04% of the total groundwater monitoring data. Figure 5 indicated that large groundwater depletion was detected in the north part of Beijing Plain, while the majority of sites where the groundwater level slightly decreased or revived located in the south Beijing Plain.

4.3. Correlation Analysis. The results showed that the groundwater depth had significantly high correlation coefficient with agricultural water use, industrial water use, domestic water use, and environmental use (correlation efficient > 0.8 and p value < 0.05). Particularly, among the four highly related predictors, the groundwater depth was positively correlated with agricultural and industrial water use, while the other two showed negative relationship (Table 4). These predictors were highly correlated with each other ($p > 0.6$). For instance, the four water sectors were highly interrelated. The precipitation was positively related with inflow, outflow, surface water resources, and groundwater resources. Obviously, the fluctuation of groundwater depth was affected by the coefforts of these variables. Therefore, the multifactor analysis was used to study the co-contribution of these predictors to the variation of groundwater depth. The correlation coefficients and the significant level were displayed in Table 4.

4.4. Factor Analysis. It is difficult to make predictions on groundwater depth using the raw data of the predictors. Therefore, factor analysis was conducted to the 9 predictors of the groundwater depth by using the Maximum Likelihood Dimensionality Reduction method. Factors without multicollinearity were generated, based on the raw variables after the reducing dimensionality. Absolute loading of each variable which is over 0.7 is categorized as a factor.

Results showed that three factors have been selected (Table 5). Factor 1 was composed of agricultural water use, industrial water use, domestic water use, and environmental use. All the variables in factor 1 have shown highly relevant relationships with groundwater depth. These variables are highly connected with social water demand. Thus, factor 1 was named as "demand factor." Factor 2 included surface water storage, groundwater storage, and precipitation amount, which was concluded as "supply factor." Factor 3 consisted of the outflow of the region, which was nominated as "loss factor." The eigenvalues of the factors were 3.563, 2.910, and 1.632, respectively. The values indicate that the first factor contributes the largest explanatory importance to the variables, followed by the remaining two in sequence. The proportion variance of these factors shows the same results, which are 0.396, 0.323, and 0.181, respectively. The accumulative variance is of 90.5%.

5. Discussion

5.1. The Great Drop Period Deserves Concentration. Results showed that a sharp decline has been witnessed from 2001 to 2010. Actually, the groundwater depth in Beijing was normally less than 10 m in the early 1980s [9]. However, the decreasing speed of the groundwater level had been accelerated from 0.3 m/year in 1980s to 0.5 m/year in 1990s and then to 1.2 m/year in 2000s. The groundwater depth reached 24.94 m in 2010 [9]. The last period was named as "the great drop" for its largest decreasing extent. Reports have also pointed out that the North China Plain, where Beijing is located, has experienced an overpumped period since 1970s and many groundwater depression cones were formed [38].

Table 4: Correlation coefficient of groundwater depth and its predictors.

	Qin	Qout	SWR	GWR	Pa	AWU	IWU	DWU	EWU
Qin	1								
Qout	**0.92***	1							
SWR	**0.84***	**0.79***	1						
GWR	0.41*	0.50*	0.58*	1					
Pa	**0.67***	**0.64***	**0.86***	**0.82***	1				
AWU	0.47*	0.32	0.51*	−0.30	0.17	1			
IWU	0.49*	0.44*	0.34	−0.34	0.05	**0.83***	1		
DWU	−0.45*	−0.27	−0.56*	0.22	−0.23	**−0.92***	**−0.64***	1	
EWU	−0.23	−0.13	−0.21	0.43*	0.05	**−0.84***	**−0.82***	**0.74***	1
GWD	0.56	0.42	0.55	−0.26	0.23	***0.97****	***0.87****	***−0.90****	***−0.81****

*$\alpha = 0.05$.

Table 5: Loadings of variables to each factor.

	Factor 1	Factor 2	Factor 3
Qin	0.301	0.574	0.686
Qout	0.131	0.526	**0.837**
SWR	0.36	**0.86**	0.351
GWR	−0.434	**0.782**	0.175
Pa		**0.905**	0.192
AWU	**0.978**	0.128	0.149
IWU	**0.788**	−0.124	0.482
DWU	**−0.901**	−0.27	
EWU	**−0.864**	0.163	−0.122
Eigenvalue	3.563	2.910	1.632
Proportion variance	0.396	0.323	0.181
Cumulative variance	0.396	0.719	0.901

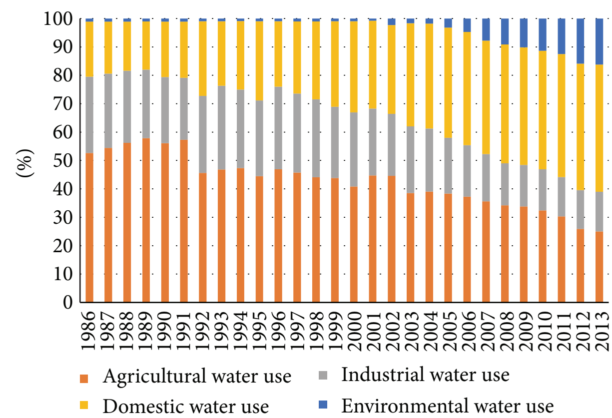

Figure 6: Water consumption composition in Beijing from 1980 to 2013.

This has caused severe water shortage, especially for the irrigated land which relies on groundwater, and derived ecoenvironmental problems relating to low groundwater level [39, 40].

Factor analysis and correlation analysis indicated that the groundwater depth showed high linear correlation with water usage in four social sectors but exerted less correlation with inflow, water storage, precipitation, and outflow. These predictors in the regional water balance model could be categorized as three classes: (i) demand factor, including water uses; (ii) supply factor, including water storage and precipitation; and (iii) loss factor, including regional outflow. The contributions to the total variance were 39.6%, 32.3%, and 18.1%, respectively. Therefore, it can be inferred that the water usage should be the major influencing factor to the variation of groundwater depth, followed by the water supply. The water loss from the regional water system has less influence.

Water usage becomes the main contribution to the variance of groundwater level because it switched its dependence from surface fresh water to groundwater since the 1980s. Miyun and Guanting reservoir lose the ability to supply enough water gradually because their water amount has reduced to 10 percent of the original storage capacities. Moreover, Guanting reservoir was too polluted to supply water [41]. A new water usage policy has therefore been initiated to cut back water supply to irrigation from Miyun and Guanting reservoir in order to guarantee domestic water supply since 1980s [41]. This triggered the urgent need of groundwater as an alternative water source for irrigation [41].

Agriculture took 64% of the water consumption in Beijing in the 1980s. This ratio decreased to 25% in 2013 gradually. We found out that the groundwater level was declining, while the agricultural water use was also decreasing. Though many researchers believed the groundwater variation was highly linked to irrigation water use, groundwater depth in Beijing Plain may exert converse answers [13, 42, 43]. The water consumption from ongoing urbanization would gradually cut off agricultural water use, which will account for less proportion in the future.

However, the domestic and environmental water demands were correlated with the population increasing and extending of human need. Therefore, we proposed that the depletion of groundwater should be attributed partially to the expanding of population growth. The domestic water use, originated from 8% of the total in the 1980s, has reached 45% in 2013 (Figure 6). This drastic change indicated the variation of the water use composition and implied the transformation of the social structure in the past three decades. This may be attributed to the population booming in Beijing. The resident population has been increasing from 13.64 million in 2000 to 20.19 million in 2011, with an increasing rate of 4.365% per year. In addition, with more floating population, the population on water resources is more severe than the previous years.

5.2. Spatial Variation of Groundwater Level in Beijing Plain Exerts More Information. Though a general sharp decreasing of groundwater level happened in the great drop period, not all the regions in Beijing Plain showed the same trend. The NBP had a similar trend, while the south part did not. The most severe groundwater depletion was identified in the CBP and partial NBP. The lowest groundwater level was detected in the CBP, near lower reaches of the Miyun reservoir. The majority of irrigated land is distributed in this region, which depends on groundwater totally [41]. Zhu et al. (2015) also pointed out that the groundwater withdrawal had triggered the continuous increasing of land subsidence in the NBP from 2003 to 2010 [43].

It should be noted that only 8.57% of the monitoring sites suffered from the largest decreasing. And 19.04% sites endured a decreasing extent of more than 15 m. Most of the areas faced the fact of the decreasing of the groundwater level being less than 15 m. That means that the depletion in NBP may be majorly responsible for the groundwater deterioration, which deserves more focus in future groundwater management.

However, a reviving trend was recognized in some monitoring sites in the great drop period, especially in Fangshan and Tongzhou districts. It can be explained by less irrigated land in the SBP than NBP and less population in the SBP than CBP, which indicates a lower abstraction rate than the recharge rate of groundwater. Therefore, the groundwater level in SBP did not decrease as in the NBP and CBP. Yang et al. (2009) also have confirmed that the SBP area showed less groundwater overdraft than the NBP and CBP areas [44]. This illustrates the effect of local impact factor on shaping the groundwater system.

6. Conclusion

The spatiotemporal variation of groundwater level is essential to water resources management in Beijing, as groundwater will still comprise the majority of water source in the next decade. The following conclusions could be drawn through this study:

(1) During the period of 2001 to 2010, the groundwater level fell from 24.76 m to 16.35 m, with an annual changing rate of −0.841 m per year. This trend is statistically significant according to the Mann-Kendall test results.

(2) There exists large spatial difference of groundwater level within Beijing Plain. Groundwater depth in north part of Beijing Plain was larger than the south part. A northwest to southeast dropping gradient of groundwater level was noted from the spatial variation plots. Among the sampling sites, 19.04% of the total were confronted with groundwater level decline of more than 15 m, while the other 29.52% shared the decreasing of groundwater level within 5 m. Most of the sites were located in the NBP. Due to the enormous amount of irrigated groundwater demand, the downstream of Miyun reservoir, located in NBP and CBP partially, faced most severe groundwater depletion. Many areas in the SBP (15.24% of the total samplings) presented a recovery phenomenon of groundwater level during the period of 2001 to 2010. It is assumed that the low development in this region placed less pressure on groundwater than its north counterpart. Therefore, we deduce that the local impact factor may play a more important role in the process.

(3) Water usage of four sectors was highly related to groundwater level. The precipitation, inflow, outflow, and water storage were not corresponding to the groundwater level. The variables in the model were categorized in three classes based on factor analysis: (i) "demand factor" (including water use of the four sectors), (ii) "supply factor" (including surface water storage, groundwater storage, and precipitation), and (iii) "loss factor" (including outflow). The contributions of the three factors to total variance were 39.6%, 32.3%, and 18.1%, respectively. The domestic and environmental water usage is steadily increasing which will be majorly responsible for the groundwater depletion.

(4) Nevertheless, this study has some limitations to be addressed in the future work. Firstly, more data should be filled within the database. Seasonal or monthly data would be a help in determining more details of the variation. Although the factor analysis was conducted to detect the shared characteristics, the contribution of each variable in the three factors was not clear yet. Future studies may fix this by focusing on the groundwater depth/level and each of these variables. Secondly, further studies should be conducted in spatial analysis to explain the differences within Beijing Plain by collecting more spatial data of the driving factors. For instance, the distributed water consumption data of each district could offer better understanding of the spatial variation of groundwater level.

Conflict of Interests

The authors declare no conflict of interests.

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