Groundwater level response to hydrogeological factors in a semi-arid basin of Beijing, China

Xiaomin Gu, Yong Xiao, Shiyang Yin, Jingli Shao, Xingyao Pan, Yong Niu and Junxiong Huang

ABSTRACT

In this study, the mode of groundwater level fluctuations is analyzed by statistical approaches for 51 monitoring wells located in a semi-arid basin in Beijing from 1998 to 2013. Firstly, a geostatistical method was performed to characterize the spatial and temporal behaviors of data sets and analyze the responding mechanism of groundwater level to hydrologic features using the Geostatistics Module of ArcGIS software. Secondly, multiple statistical methods were applied to classify groundwater hydrographs with similar fluctuation patterns. The results show that the spatial distribution of groundwater level is affected by natural factors (rainfall and temperature) as well as human activities. Combined with the method of principal component analysis, the hydrologic features of groundwater level can be classified into three groups and the dynamic characteristics of each group under different hydrogeology conditions are also different. Furthermore, a cross-correlation analysis was applied to investigate the groundwater level response to natural processes and human activities. This study provides a series of effective methods for evaluating the long-term series fluctuation features of groundwater level and its response to hydrological factors, as well as the scientific basis for the reasonable configuration and utilization of groundwater resources in arid and semi-arid regions.

Key words | arid and semi-arid region, geostatistics interpolation, groundwater level, hydrologic factors, multivariate statistics

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INTRODUCTION

Due to the ceaseless development of social economy, the deficit of groundwater resources has become a global problem (Solomon 2015). The excessive exploitation in aquifers has caused the continuous decline of groundwater level and has also led to a series of secondary geological disasters. Groundwater level is one of the most important hydrologic elements of the aquifer, the spatio-temporal variability analysis of which could reveal the relevant information of the groundwater system (Machiwal *et al.* 2012). Due to the scarce rainfall, groundwater resources are very limited in arid and semi-arid regions. The increasing rise of demand on groundwater has posed a threat to the sustainability of groundwater resources. In order to reasonably utilize groundwater resources, groundwater level monitoring shall be conducted comprehensively in the long term (Esquivel *et al.* 2015).

Currently, a variety of statistical analysis methods based on groundwater level records have been considered for groundwater depth forecasting and analysis, such as principal component analysis (PCA) (Yu & Chu 2012), trend analysis (Mendizabal *et al.* 2012), artificial neural network methods (Hosseini-Moghari & Araghinejad 2015), time-series analysis, such as correlation and spectral analysis (Aflatooni *et al.* 2011), as well as the moving average

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method (Mirzavand & Ghazavi 2014). The features of the spatial-temporal distribution of groundwater level are affected by various factors, including groundwater exploitation, climate change (Venencio & García 2011), the interaction with the surface water and tidal action in coastal aquifers (Wu *et al.* 2010). The groundwater system, which is subject to the joint effect of natural conditions and anthropogenic factors, shows different patterns of groundwater level fluctuations in different areas of the alluvial plain. Therefore, in order to reveal the amplitude of groundwater level variation in a hydrologic year, the relevant hydrology factors shall be applied to the different hydrogeologic conditions (Toews *et al.* 2009).

However, the groundwater monitoring network is composed of only a few observations in many cases, the direct application of multivariate statistical analysis could not reflect precisely the distribution characteristics of groundwater level. Therefore, the interpolation of geostatistics shall be utilized to reveal the spatial distribution characteristics of groundwater level (Venencio & García 2011).

The geo-statistics are mainly applied into the unbiased optimal estimation for the regional variables (Ghazi *et al.* 2014) and the structural characteristics analysis of time-space through variogram models. Among them, the interpolation of geo-statistics is a method to estimate the data in a contiguous area and predict the unknown points (the information of which is missing or cannot be obtained) with limited data sets (Triki *et al.* 2013). This method has been widely applied in meteorology, hydrology, soil and other fields (Nikroo *et al.* 2010; Uyan & Cay 2013; Triki *et al.* 2014; Ciotoli *et al.* 2015).

Based on the Statistical Package for Social Sciences (SPSS) data analytic software and ArcGIS Geostatistics Module, this paper focuses on the pattern of groundwater level fluctuation in the Yanqing basin of Beijing, applying PCA to classify the groundwater hydrographs with similar features. The characteristics of spatio-temporal distribution were analyzed and the spatial distribution features of the groundwater level at unknown points were predicted based on the semi-variagram function model. Furthermore, the responses of different groundwater hydrogeologic types to temperature, rainfall and human activities were investigated to obtain the relationship between different hydrologic factors and the pattern of groundwater level fluctuations.

STUDY AREA

Yanqing Basin, located in northwestern Beijing, China, is surrounded by mountains in three directions and is adjacent to Guanting Reservoir (Figure 1). The coverage area is 522.34 km^2. The annual mean temperature is 8.8 °C, the annual average rainfall is 439 mm and the mean evaporation is 400 mm/a. The aquifers can be classified into two major systems, namely the unconfined aquifer system in the piedmont area and confined aquifer system in the front edge of the alluvial fan. The former changes from a single layer to a multi-layer of sand and gravel. The latter is a multi-layer structure with a fine sand layer covering it, and the underlying strata is 2–3 layers of sand and gravel (Figure 2).

METHODOLOGY

Data collection

Since the 1980s, due to the scarcity of rainfall and the increasing demands on domestic and industrial purposes in Yanqing basin, the groundwater level continues to decline because of the excessive exploitation. In order to monitor the amount of dynamic fluctuation of groundwater resources, a monitoring network for the groundwater level was established and observation was conducted every 5 days. This research collects the monitoring data including the detailed yearly average groundwater level information in the 51 wells for the time period from 1998 to 2013 (the monthly record exceeding 15 years), as well as the average monthly rainfall and the average temperature from 1998 to 2013. The groundwater level data were provided by the Water Supply Bureau of Yanqing and the monthly rainfall and temperature data were provided by the meteorological station and precipitation station of Yanqing (Figure 1).

The annual average fluctuation trend of the groundwater level in the 51 monitoring wells is summarized in Table 1.

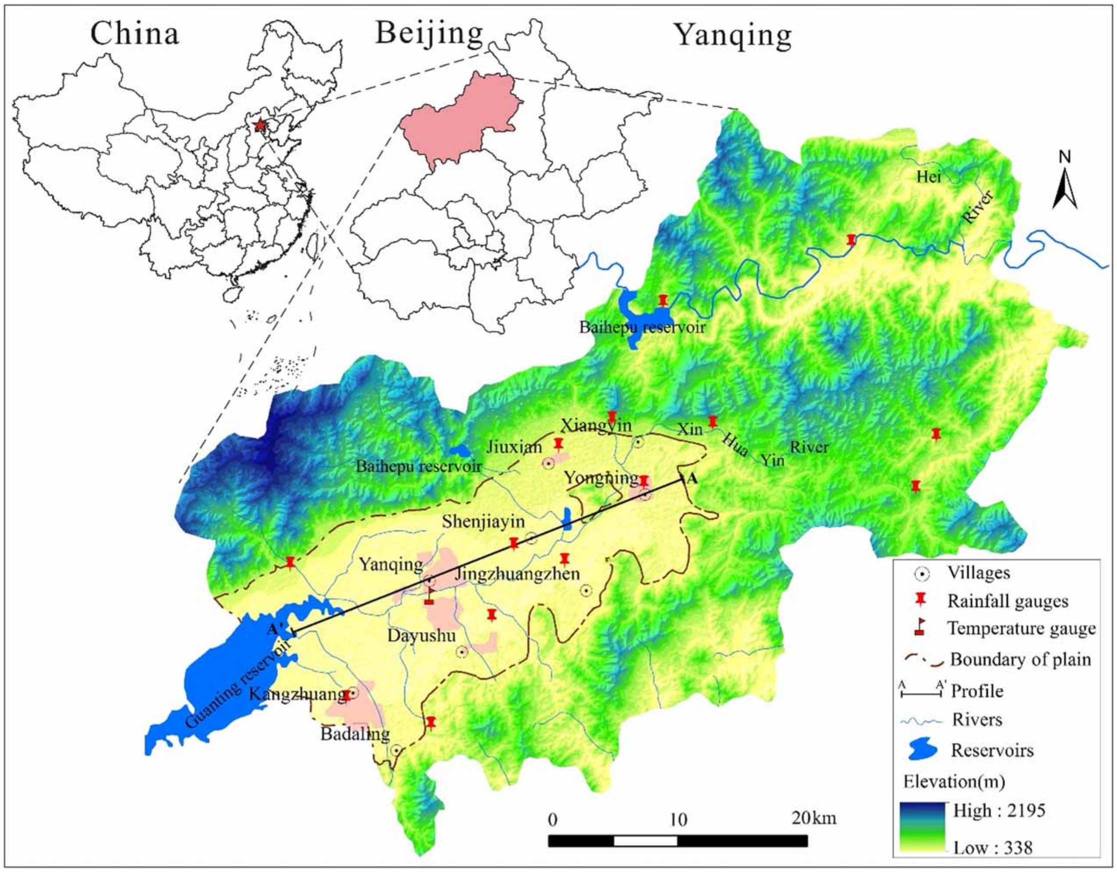

Figure 1 | Location of study area.

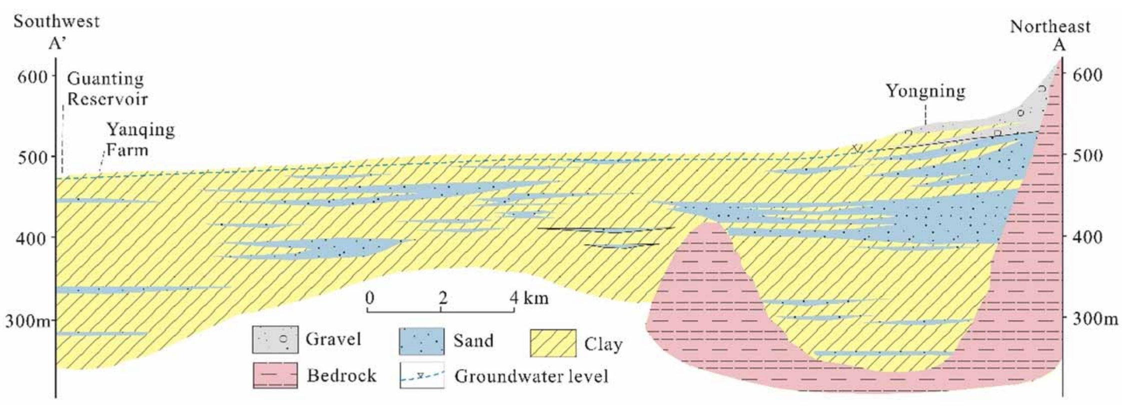

Figure 2 | A-A′ profile of study area.

During the 16 years, the groundwater level shows a continuous trend of decline. The drawdown is related to the reduction of natural recharge amount and excessive exploitation. However, the groundwater level of some monitoring wells shows a stable state or slows rising trend, which is probably related to recharge and regulating effect of the reservoir in the southwest part of the study area (Bai 1987; Seeboonruang 2012).

Table 1 | Information of observation wells and results of PCA

		Result of PCA					Result of PCA		
Well number	Average annual water level fluctuation (m/a)	PC1	PC2	Groups identified by PCA	Well number	Average annual water level fluctuation (m/a)	PC1	PC2	Groups identifid by PCA
1	−0.57	0.68	−0.19	A	27	−0.68	0.73	0.39	B
2	−0.14	0.65	−0.20	A	28	−0.84	0.63	0.42	B
3	−0.21	0.82	−0.09	A	29	−0.72	0.58	0.33	B
4	−0.67	0.49	0.24	B	30	−0.39	0.62	0.31	B
5	−0.02	−0.68	0.35	C	31	0.99	−0.58	0.12	C
6	−0.38	0.78	0.22	B	32	0.17	−0.45	0.28	C
7	−0.59	0.12	0.34	B	33	−0.42	0.42	0.31	B
8	−0.50	0.73	0.21	B	34	−0.31	0.11	0.12	B
9	−1.19	0.56	0.27	B	35	−0.24	0.69	−0.52	A
10	0.54	−0.32	0.24	C	36	−0.31	0.55	0.12	B
11	−0.56	0.18	0.28	B	37	−0.27	0.78	−0.08	A
12	−0.21	0.51	−0.19	A	38	−0.72	0.73	−0.27	A
13	−0.07	0.42	−0.49	A	39	−0.01	0.61	−0.42	A
14	−0.39	0.83	0.48	B	40	−0.44	0.39	0.29	B
15	−0.21	0.67	0.38	B	41	−0.07	−0.52	0.33	C
16	−0.42	0.61	−0.08	A	42	−0.55	0.78	0.29	B
17	−0.09	0.42	−0.18	A	43	0.36	−0.29	0.08	C
18	0.00	−0.62	0.27	C	44	−0.08	0.73	−0.15	A
19	0.84	−0.5	0.14	C	45	−0.16	0.71	−0.39	A
20	−0.45	0.32	0.22	B	46	−0.65	0.52	0.31	B
21	−0.49	0.49	0.56	B	47	−0.58	0.76	0.52	B
22	−0.25	0.52	−0.52	A	48	−0.51	0.48	0.39	B
23	−0.18	0.58	−0.32	A	49	−0.08	−0.72	0.29	C
24	−0.36	0.82	−0.01	A	50	−0.16	−0.21	0.16	C
25	−0.46	0.83	0.32	B	51	−0.42	0.36	0.40	B
26	−0.51	0.34	0.36	B					

The monthly rainfall data are computed by summing the amounts of daily precipitation provided by nine rainfall gauges which are adjacent to the monitoring wells. The annual distribution of precipitation varies greatly over the years, with an average rainfall of 437.6 mm. The rainfall in the wettest year and the driest year are 528.1 and 381.7 mm, respectively (Figure 3(a)). The rainy season is from June to October, and the maximum amount of rainfall can reach 180 mm, while in the dry season from November to May, the rainfall is basically less than 20 mm (Figure 3(b)). The monthly average temperature is calculated by the daily highest temperature and the lowest temperature. From 1998 to 2013, the average temperature was 12.4 °C, and the highest monthly average temperature was 28.06 °C (Figure 3(d)). Between 1998 and 2008, the monthly average temperature was 13 °C (Figure 3(c)). Since 2009, the temperature has descended gradually.

Research methods

The approaches applied in this study are as follows: (1) apply the PCA to classify the different patterns of groundwater hydrologic features; (2) obtain the spatio-temporal variation features of the groundwater level using the Kriging

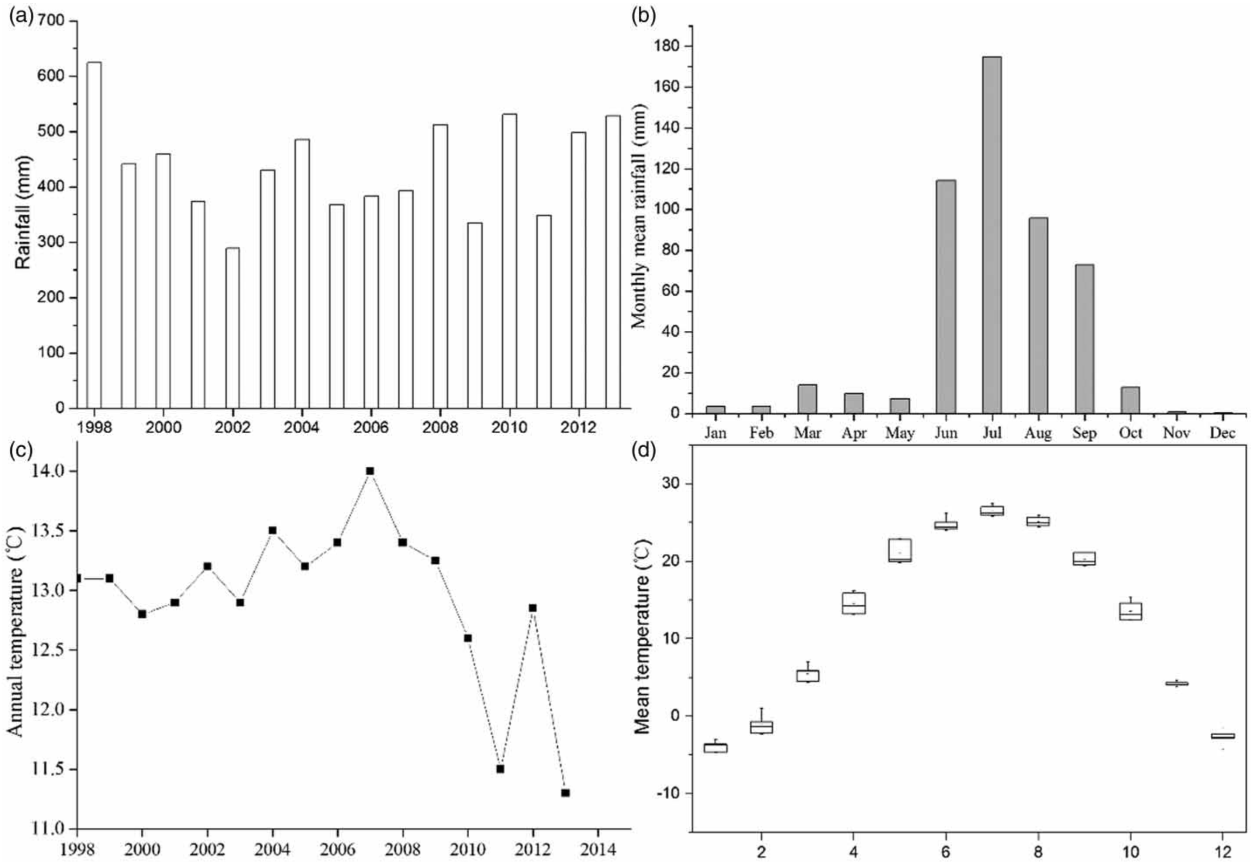

Figure 3 | (a) Bar graph of the annual average rainfall from 1998 to 2013; (b) bar graph of monthly average rainfall; (c) broken line graph of annual average temperature from 1998 to 2013; (d) box plot of monthly average temperature from 1998 to 2013.

interpolation method and identify the factors influencing the groundwater level fluctuation; (3) establish the cross-correlation analysis to evaluate the response to rainfall, temperature and human activities by groundwater level fluctuation.

Multivariate analysis

The multivariate statistical analysis was conducted to analyze the monthly monitoring data of groundwater level by PCA. PCA is known as a statistics method and has been used widely in hydrology and other fields (Lischeid *et al.* 2010; Liu *et al.* 2011; Yu & Chu 2012). It is a procedure aimed at reducing the dimensionality of multivariate data while accounting for as many of the variations in the original data set as possible. This method could identify the information overlapping in the water level variables, thus reducing the interference of unnecessary information (Arslan 2013). The software SPSS ver. 20 was applied to analyze the sample data, which contains powerful tools for statistical analysis of data and has been widely used for its friendly interface and convenient operation.

Geostatistical approach

Semi-variogram is a unique function of geostatistical analysis (Gundogdu & Guney 2007), which can be used to describe the spatial variability of groundwater level. Geostatistics Module in ArcGIS ver. 10.0 was applied to analyze the data, which is widely used to analyze and predict the values associated with spatio-temporal phenomena. Assuming the mean value of random function being stable, the value of this function is only relevant to the distance between the samples, the semi-variogram $\gamma(h)$ could be defined as half of the incremental variance of random function $Z(x)$.

$$\gamma(h) = \frac{1}{2}E[Z(x) - Z(x+h)]^2 \quad (1)$$

where $\gamma(h)$ is the variogram model; $Z(x)$ is the random function; h is the distance between samples. $Z(x)$–$Z(x+h)$ is the spatio-temporal distribution difference of variables caused by h. When the time series of piezometric head is considered, Z is the groundwater level, and h is the time lag of the measured values.

Cross-correlation analysis

Generally, cross-correlation analysis, $z_{xy}(k)$, is used to analyze the causal relationship and the correlation degree between time series of input, (x_t), and time series of output, (y_t) (Krishan *et al.* 2014). The major research object of this paper is time series of lag effect, namely the retardation effect of groundwater level fluctuation to temperature and rainfall, therefore, the cross-correlation analysis shall be used to determine the influence of the two climate factors to the fluctuation of groundwater level, see Equation (2) (Song & Zemansky 2012):

$$\rho_y(k) = \frac{E[(x_t - \mu_x)(y_{t+k} - \mu_y)]}{\sigma_x \sigma_y} \quad (2)$$

where $\rho_y(k) =$ cross-correlation at time lag k, $k = 0, \pm 1, \pm 2 \ldots \pm n$ time lag between the two series, $x_t =$ observed rainfall at time t, $y_t =$ observed water level at time t, $\mu_x =$ mean value of rainfall series, $\mu_y =$ mean value of water-level series, $\sigma_x =$ standard deviation of rainfall series, $\sigma_y =$ standard deviation of water-level series. Significant correlations at the 95% confidence level are taken to be those greater than the standard error $\approx 2\sqrt{N}$, where N is the number of values in the data set. This is effectively testing the hypothesis of no correlation and assumes that the variance is finite and normally distributed about a mean of zero (Keane & Adrian 1992).

In this study, the auto-correlation analysis was applied to identify the structure and composition of the monthly rainfall, temperature and groundwater level time series separately, the time lag and the significant correlations were identified by the cross-correlation analysis.

RESULTS AND DISCUSSION

Classification of groundwater hydrographs

Two major factors have been considered in the PCA of 51 hydrograph records, with the eigenvalues >1 and the summing cumulating ≥85% of the total variance in the data sets. The results of the rotary load factors related to each factor are shown in Table 1.

PC1 and PC2 account for 81.9 and 5.6%, respectively. The scores for the hydrological factors related to PC1 are shown in Figure 4(a) and 4(b). The relationships between the component load of each monitoring well and PC1 (PC2) signify that the monitoring wells of groundwater could be classified into three groups: Group A has loadings greater than 0.5 on PC1 and smaller than 0 on PC2, Group B has loadings greater than 0 on both PC1 and PC2, Group C has loadings smaller than 0 on PC1 and greater than 0 on PC2.

The monitoring wells of Group A are located mainly at the recharge area of the piedmont area. The hydrograph of the groundwater level shows a regular groundwater drawdown with an annual cyclic variation and describes the behavior of shallow wells, which is similar to the trend of the hydrograph for PC2 (Figure 5(b)). Monitoring wells of Group B are located mainly at the over-exploitation area, and indicate the similarity of the groundwater level hydrograph and scores hydrograph for PC1 (Figure 5(a)), which shows a steadily decreasing trend. The groundwater level fluctuation of Group B is relatively large but contains little high frequency variation. Located mainly at the discharge area near the reservoir, the groundwater level of Group C stays stable and presents a rising trend for some monitoring wells.

Analysis of the spatio-temporal variability of groundwater level

The annual groundwater level satisfied normal distribution, and there was no apparent dominant trend observed.

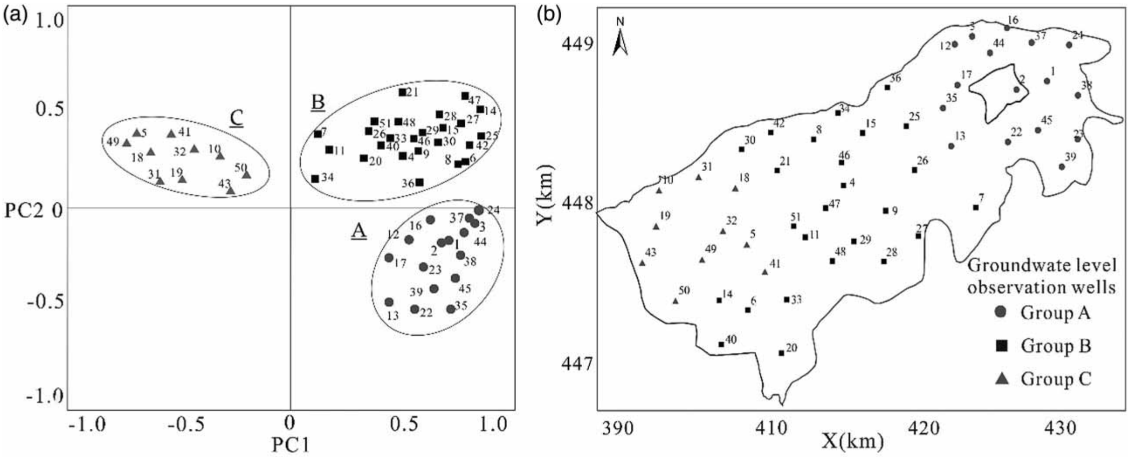

Figure 4 | (a) Scatter diagram of the comparison of scores by PC1 and PC2 respectively; (b) classification of monitoring wells for groundwater in the region under research.

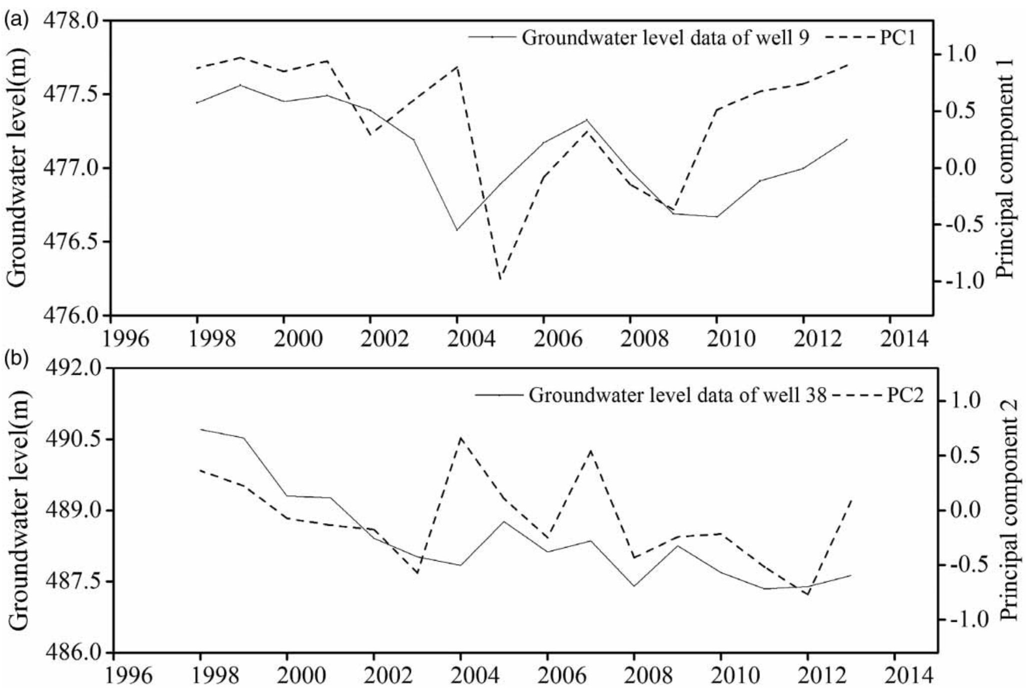

Figure 5 | Comparison graph of the PC time-series and hydrology time-series: (a) #9 of groundwater level monitoring well; (b) #38 of groundwater level monitoring well.

Therefore, ordinary kriging was appropriate for interpolation. Based on the geostatistics module in ArcGIS ver. 10.0, the groundwater level contours of Yanqing Basin (Figure 6) in 1998 and 2003 as well as the groundwater level drawdown (Figure 6) from 1998 to 2003 could be obtained. Comparing the groundwater level in 2013 with that in 1998, the trend of groundwater flow is similar. The groundwater level drawdown is large in the central basin because of over-exploitation of the Yanqing water plant and Dayushu water supply center, the capacities of which are 2.8×10^4 and 0.5×10^4 m^3/d, respectively, while the southwestern part is mostly agricultural and the exploitation amount is relatively small. Meanwhile, the groundwater was recharged by irrigation water infiltration and surface water seepage from Guanting Reservoir, as a result, the groundwater level fluctuation in the southwestern part is small.

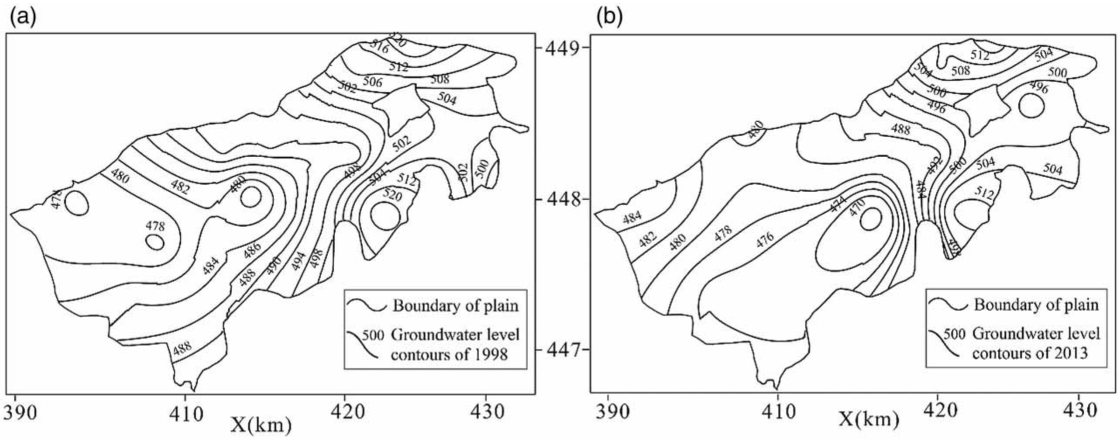

Figure 6 | Groundwater level contours of Yanqing measured in (a) 1998 and (b) 2013.

According to Figure 7, the study area can be classified into three different regions: the piedmont recharge area, over-exploitation area at the center of the basin, and the discharging area at southwest of the basin. Combined with the ordinary kriging method of the geostatistics module, the statistics analysis of the groundwater level data from 1998 to 2013 was conducted. As shown in Table 2, the sill ratios show a generally increasing trend between 1998 and 2013, indicating that the degree of influence by humans and the spatial correlation has decreased gradually. From 1998 to 2004, the sill ratios of groundwater level are relatively small, suggesting that the influences on the groundwater level by terrain, rainfall, sedimentary structure, hydrogeologic conditions and other factors are relatively large, and the spatial correlations are strong.

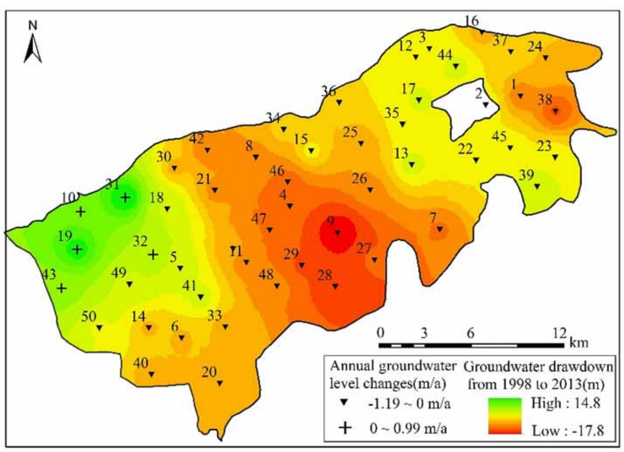

Figure 7 | Distribution of shallow groundwater drawdown in plain from 1998 to 2013.

Table 2 | Semi-variance function model parameters of groundwater level (1998–2013)

Year	Nugget	Partial sill	Sill value	Sill ratio
1998	0.17	0.78	0.95	0.18
1999	0.2	0.74	0.94	0.21
2000	0.21	0.73	0.94	0.22
2001	0.22	0.72	0.94	0.23
2002	0.23	0.71	0.94	0.24
2003	0.27	0.68	0.95	0.28
2004	0.24	0.69	0.95	0.25
2005	0.29	0.66	0.95	0.31
2006	0.31	0.65	0.96	0.32
2007	0.34	0.61	0.95	0.36
2008	0.38	0.58	0.96	0.4
2009	0.41	0.54	0.95	0.43
2010	0.46	0.49	0.95	0.48
2011	0.45	0.51	0.96	0.47
2012	0.43	0.53	0.96	0.45
2013	0.41	0.53	0.94	0.44

Due to the continuous development of social economy, groundwater exploitation has increased ceaselessly, and the sill ratios are also increased. The spatial correlation decreases due to over-exploitation. Since 2010, the sill ratios have shown a trend of slow decline, implying that the excessive exploitation is under control to some extent, and the spatial correlation has also been reinforced. It indicates that the groundwater level fluctuation is not only influenced by temperature, rainfall, human exploitation and many other hydrogeological factors, but is also affected by anthropogenic factors with the increased utilization of groundwater resources.

Cross-correlation of air temperature, rainfall and groundwater level data

Cross-correlation analysis was performed with rainfall and temperature as the input variables, and groundwater level as output variable, using monthly time series data collected from January 2008 to December 2013. The significance level of cross-correlation analysis was 0.22 (Figure 8).

Figure 8(a)–8(c) compares the time series data of rainfall and temperature with the cross-correlation for groundwater level series of wells 38, 9 and 10. The results show that, as for well 38 in the piedmont area, the groundwater level variation is more sensitive to the variation of rainfall than that of temperature. Therefore, the recharge amount variation due to the rainfall would directly cause groundwater level fluctuations, which would decrease in the dry season, and increase in the rainy season. When the exploitation is greater than the recharge amount, the groundwater level shows a trend of continuous decrease. The groundwater level variation of well 10 is more sensitive to variables in temperature than precipitation. Located at the discharge area near Guanting Reservoir, the precipitation is the main recharge source in the rainy season, while in the dry season groundwater is recharged by the seepage of the reservoir. Meanwhile, water evapotranspiration is the main discharge form in the discharge area, as a result, the cross-correlation between groundwater level and the temperature is relatively strong. The response of groundwater level variation of well 9 in the over-exploitation area is less sensitive to both temperature and precipitation, indicating that the effect of the two is smaller than the exploitation, and the groundwater level shows a continuous decrease under over-exploitation.

Table 3 lists the overall significant results ($z \geq 0.22$) with the representative time lags and the significant correlations of monitoring wells considered. The cross correlation between groundwater level and the monthly rainfall reflects that the groundwater level of the monitoring wells in the piedmont area has a significant correlation ($z \geq 0.22$) with precipitation. The corresponding time delay to the maximum amplitude is 0–4 months on average, implying that the correlation between the groundwater level and rainfall is relatively strong and the time delay is short. The time delay in the piedmont area represents the transmission time through the unsaturated zone.

On the other hand, the time lag of the responses by groundwater level to temperature and the maximum amplitude in the southwest part of the region shows that there exists a significant correlation between the two factors. The average lag time of the monitoring wells is 0–3 months, indicating that the correlation between the fluctuation of groundwater level and the temperature is relatively strong. Therefore, the groundwater level is influenced by Guanting Reservoir and groundwater is mostly discharged through evapotranspiration.

There exists weak correlation between the groundwater level in the over-exploited area and the precipitation. Meanwhile, the precipitation recharge time as well as the lag time is relatively long because of the low permeability of aquifer. Moreover, the demand on groundwater resource is large in this area, and the groundwater level fluctuation is affected by exploitation, thus the correlation with temperature or precipitation is weak.

The results of cross-correlation analysis and PCA are consistent in conclusion with further comparison. The results show that the influences of hydrologic features on the groundwater level fluctuation of Group A are small. Group A is located at the piedmont area in the northeast part of the basin, the groundwater level shows a regular drawdown with an annual cyclic variation and a trend of periodic changes. The major lithology in the piedmont area is sand and gravel and it is recharged directly by precipitation, the deficit caused by the exploitation of groundwater in dry season can be recharged in rainy season. Therefore, the correlation between the groundwater level of Group A and rainfall is relatively strong, and the lag time is short. The monitoring wells of Group B, located at the over-exploitation area in the center of the plain area, are affected by heavy exploitation. Therefore, the groundwater level shows a trend of continuous decrease, and its response to rainfall and temperature is not very obvious with a long time delay. The groundwater level of Group C, located at the discharge area, remains stable due to the seepage recharge by Guanting Reservoir. The response of the

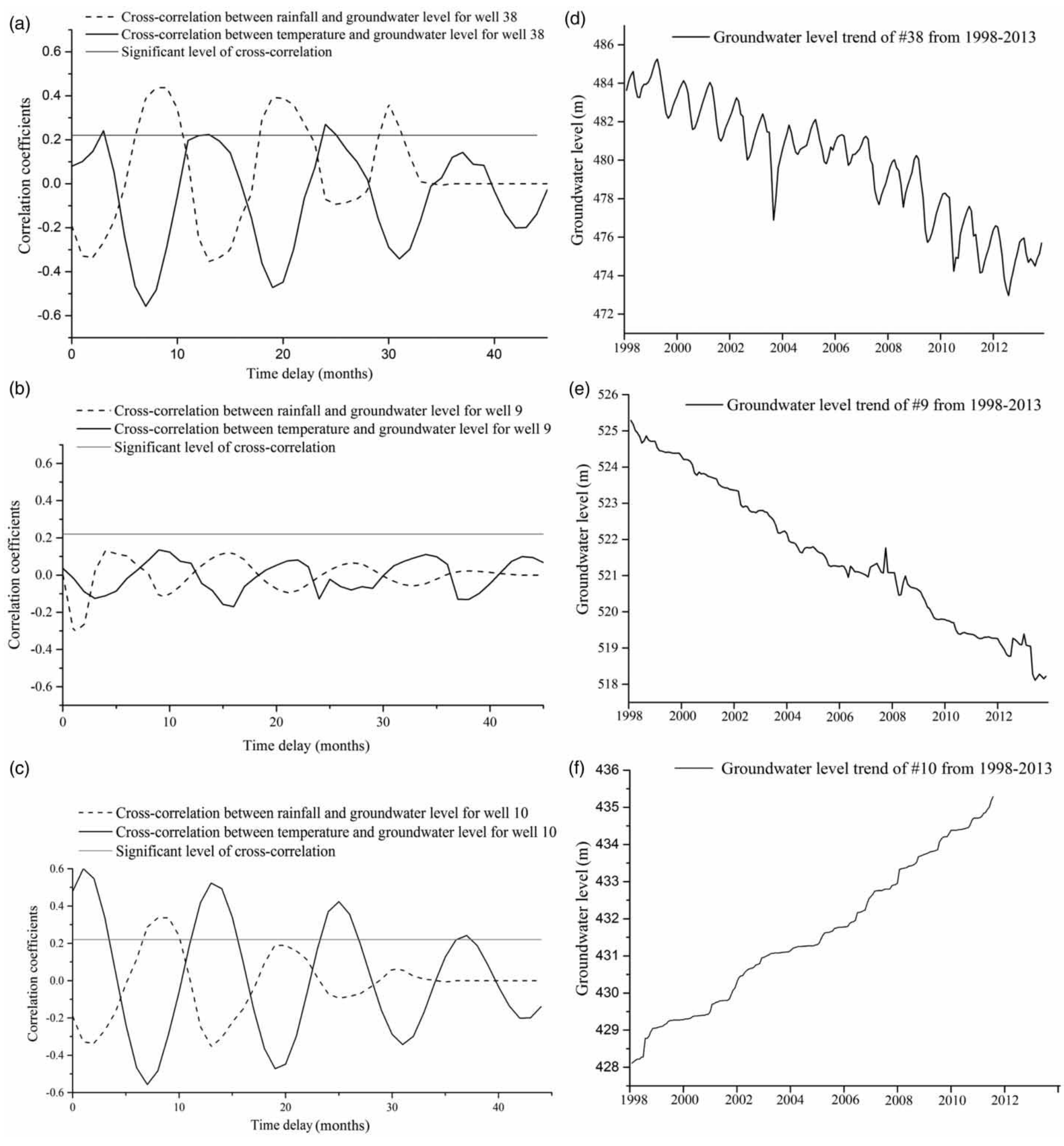

Figure 8 | Cross-correlation of groundwater levels for (a) well 38, (b) well 9 and (c) well 10 with precipitation and temperature, groundwater level trend of (d) well 38, (e) well 9 and (f) well 10 from 1998 to 2013.

groundwater level in this area to temperature is sensitive with a short time delay, which is related to evapotranspiration, and the groundwater level shows a trend of slow rising when the recharge amount exceeds the discharge amount.

CONCLUSIONS

The fluctuation of groundwater level is affected by various factors, including hydrologic and anthropogenic factors. The geostatistics method and variogram model are utilized

Table 3 | Retardation time and maximum amplitude of the response by groundwater level to rainfall and temperature

		Rainfall		Temperature	
Type	**Well number**	**Lag time (month)**	**Max correlation corrficient *z*(*k*)**	**Lag time (month)**	**Max correlation corrficient *z*(*k*)**
Group A	1	**3**[a], 4, 15	0.28	6, **7**, 8, 18, 19, 20	0.29
	2	**2**, 6, 7, 21	0.24	0, 1, 11, 12, **21**, 22, 23	0.03
	3	**0**, 1, 11, 12, 21, 22, 23	0.25		No correlation
	12	5, **6**	0.23		No correlation
	13	5, **6**, 7, 8, 17	0.41		No correlation
	17	7, **8**, 9, 19, 20, 21	0.28	2, 3, 4, 14, **15**, 16	0.41
	22	**0**, 11, 12, 22, 23	0.26	**0**, 1, 2, 13	0.39
	23	**1**, 2, 3	0.44	7, **8**, 9	0.23
	24	0, **1**, 2	0.23		No correlation
	35	7, **8**, 9	0.43		No correlation
	37	1, **2**, 3, 13, 14	0.30		No correlation
	38	**0**, 1, 2, 3, 4, 12, 13, 14	0.44		No correlation
	39	5, **6**, 7	0.26		No correlation
	44	**0**, 1, 9, 10, 11, 12	0.59		No correlation
	45	**2**, 3, 4, 14, 15, 16	0.41		No correlation
Group B	6	2, 3, 4, **14**, 15, 16	0.23		No correlation
	7		No correlation	6, **7**, 8, 9, 13, 14	0.323
	20	0, 1, 10, 11, **12**, 22	0.33		No correlation
	21	**6**, 7, 17, 18	0.265		No correlation
	25		No correlation	0, **1**, 2, 13	0.37
	26	0, 11, **12**, 22, 23	0.21	7, **19**, 20, 21	0.233
	30	7, **8**, 9, 11	0.23		No correlation
	33	5, **6**, 11, 17	0.23		No correlation
	36		No correlation	**0**, 1, 2, 11, 12, 13	0.45
	40	0, 6, 11, 12, **22**, 23	0.22		No correlation
Group C	5	0, **1**, 2, 13, 25	0.24	0, **1**, 2, 11	0.33
	10	4, **5**, 6, 7, 8, 17	0.349	**0**, 1, 2, 10, 11, 12	0.64
	18		No correlation	5, **6**, 7	0.22
	19	2, **3**, 4, 5,	0.296	0, **1**, 2, 13, 14, 15	0.32
	31		No correlation	1, **2**, 3, 4, 14, 15	0.41
	32		No correlation	**0**, 1, 11, 12, 13	0.38
	41		No correlation	0, **1**, 2	0.34
	43		No correlation	0, 11, 12, **22**, 23	0.22
	49		No correlation	0, 1, **2**, 3, 4, 12, 13, 14	0.55
	50		No correlation	1, **2**, 3	0.29

[a]Maximum time period between significant cross-correlation is indicated with bold typeface.

to describe the spatio-temporal characteristics of groundwater levels and the major hydrographs influencing the groundwater level fluctuation. The influence of human activities on the spatial correlation of groundwater level increased year by year (1998–2013). Therefore, when conducting the research on the correlations between hydrologic factors and the groundwater level fluctuation, the influences of human activities should also be considered.

PCA and cross-correlation analysis are combined to classify the different patterns of groundwater level fluctuation and analyzes their response to environmental factors. Results show that the groundwater level in the piedmont area will rise after the time delay when the precipitation increases, and the response of groundwater level is relatively obvious with a short time delay. The over-exploitation area is influenced mainly by human exploitation, and the correlation between groundwater level fluctuation and rainfall or temperature is not very obvious with a relatively long lag time. The groundwater level fluctuation in the discharge area is in a stable state, which is mainly influenced by the seepage of the reservoir and sensitivity to temperature with a short time delay.

This study provides a series of effective methods for evaluating the features of long-term series groundwater level fluctuation and its responses to hydrological factors. Meanwhile, these results provide a scientific basis for the reasonable configuration and utilization of groundwater resources in arid and semi-arid areas.

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