Review and Optimization of Groundwater Level Monitoring System in Beijing Plain

Feiran Wang:1066589

Weijia Luo: 1073885

Yining Zang:1068605

Zhechen Zhang:1074448

Zhuowei Quan:1073845

1. Review of groundwater level monitoring in Beijing Plain

1.1 Introduction of Beijing Plain

The area we study is the Beijing Plain in China. Beijing is the capital of China, and the plain area accounts for a large proportion.

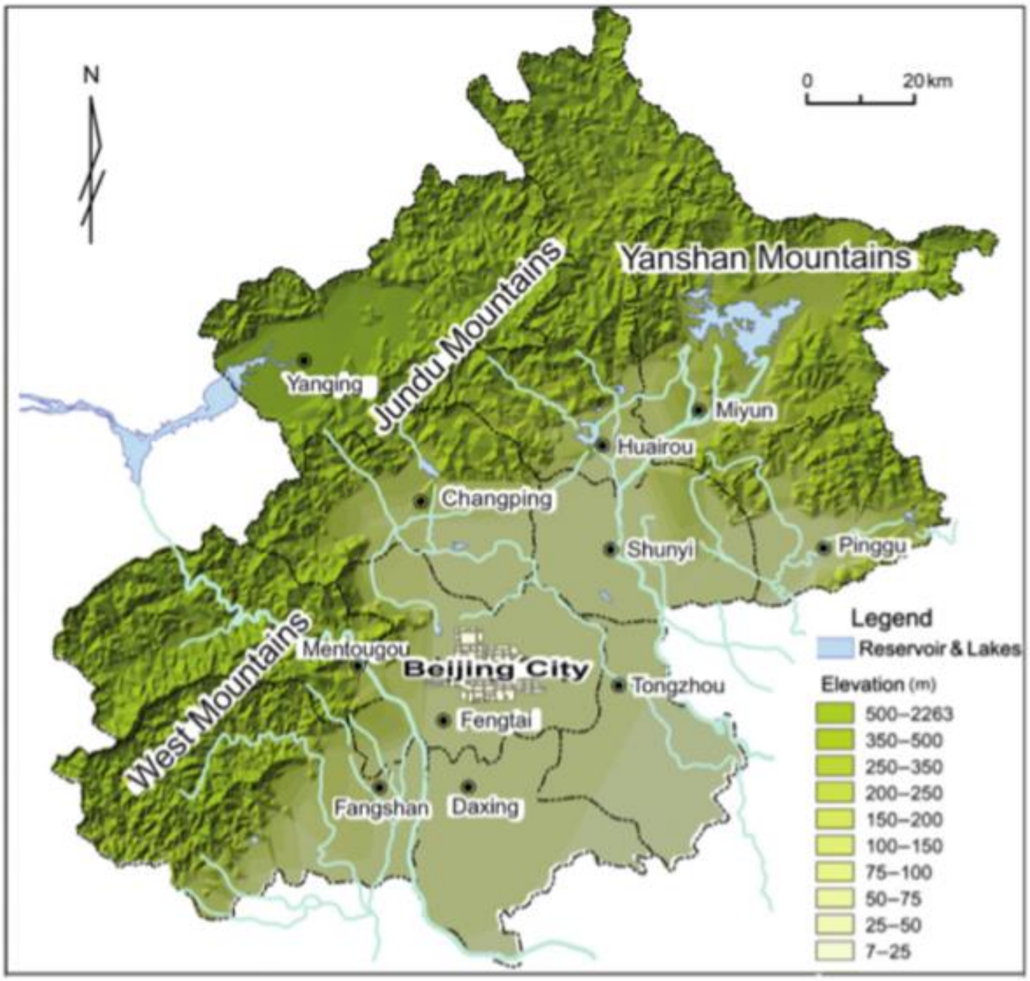


Figure 1. Topographic map of Beijing Plain

Figure 1 clearly shows the topography of Beijing, with the plain at the southeast corner.

1) Hydrogeology condition

The area of Beijing Plain is 6338 square kilometers, accounting for 38.6% of the total area of Beijing, which elevation is low and sloping toward the Bohai Sea, with an altitude of 20 to 60 meters.

2) Climate conditions

Beijing is an inland city which located in the north of China. So it is typical warm temperate semi-humid continental monsoon climate, with four distinct seasons. Spring and autumn are shorter, but the wind is relatively heavy and the weather is dry. The summer is hot and rainy, up to 39 degrees, and the winter is colder, which can be below minus. The annual average temperature is 10 ~ 13 degrees.

It has an average annual rainfall of more than 590 millimeters, which is one of the areas with the highest rainfall in North China. However, the precipitation season is very unevenly distributed. 75% of the annual precipitation is concentrated in summer, and there are often heavy rains in July and August. From 1979 to 2006, the average annual evaporation of the Beijing Plain measured at 14 stations in Beijing was 1725mm, which is almost three times the annual average precipitation.

Overall, Beijing has a resident population of nearly 20 million, resulting in huge water demand and overexploitation of groundwater. And climate variability exerts extra pressure on the groundwater reserve.

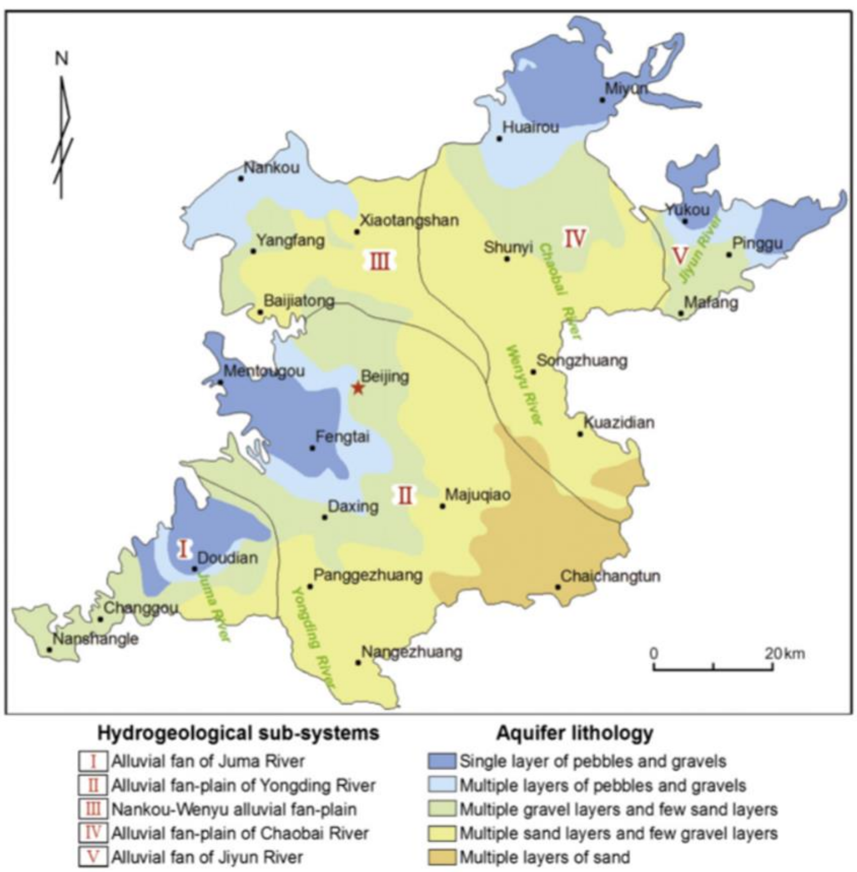


Figure 2. Hydrogeological zone map

The figure above shows the regional distribution of hydrogeology in Beijing.

Hydrology condition

Because it is located inland, Beijing has no natural lakes and only more than 80 rivers. Since the 1970s, the groundwater level in the Beijing Plain has declined significantly. Groundwater levels have decreased to historical low levels during the 8 consecutive dry years from 1999 to 2006. The total drop of groundwater levels amounts to more than 20 m since 1970's. Also, groundwater depletion has been caused either by over-exploitation or reduction of groundwater recharge. The combination of these two causes has accelerated groundwater depletion in Beijing Plain, China.

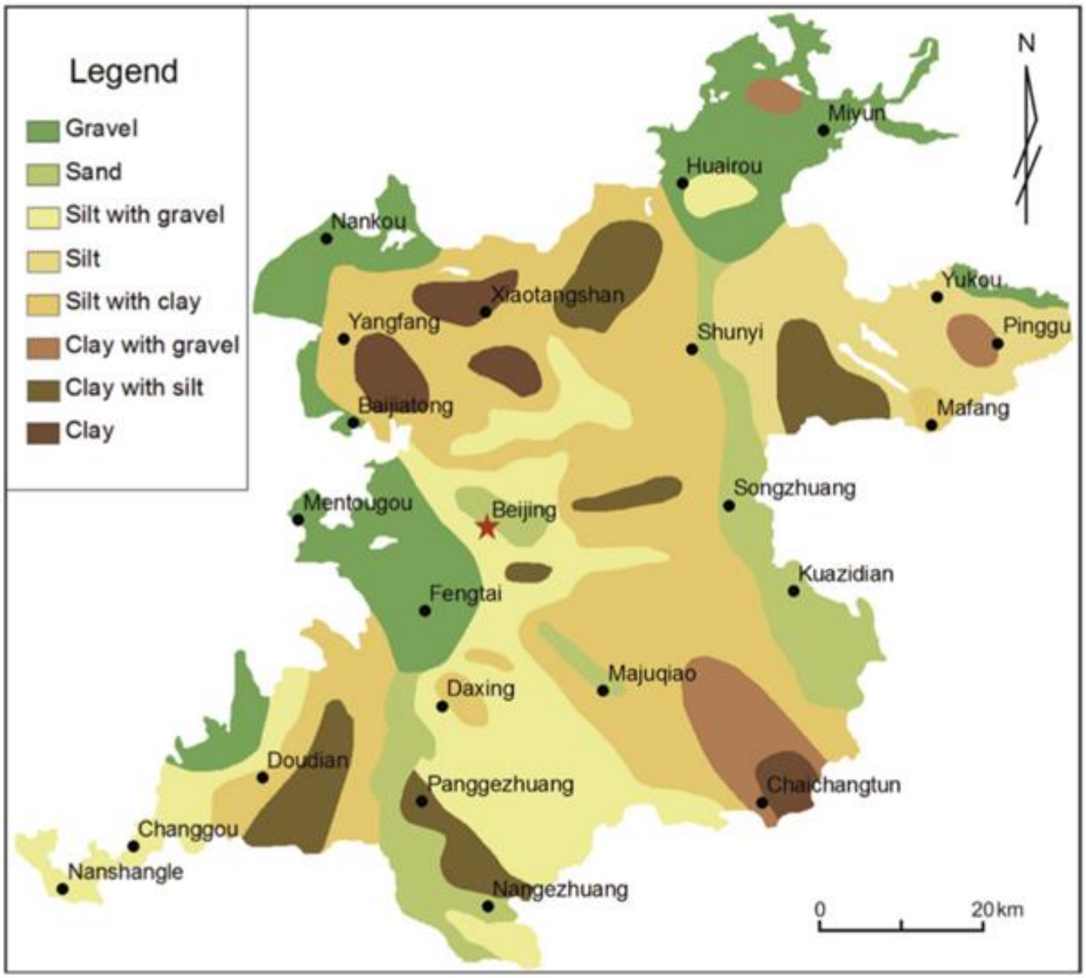


Figure 3. Unsaturated zone map

Unsaturated zone map was delineated using the water table depth map and borehole columns. The soil types of the Beijing Plain are divided into 8 categories. Figure 3 shows the distribution of soil types. Gravels and sand are mainly distributed in alluvial fans. Clay dominated soils are distributed mainly in areas between alluvial fans. We can see that gravel and silt with clay are the main ones.

1.2 The history of the groundwater monitoring system in Beijing Plain

During the 1950s developed countries started to set up the monitoring system. Most of the developing country didn’t have a system of monitoring groundwater besides China. China started groundwater monitoring since the 1950s. Until now there are 17 provinces established the groundwater monitoring system preliminarily.

Focusing on the Beijing Plain Groundwater monitoring of Beijing plain started at 1956, which around the pumping well around Beijing city. Until 1963, there were 825 wells can monitoring the groundwater level regularly, but most of them were the production wells in the countryside. But these wells have been destroyed during the revolution between 1967to 1976.

1.3 The objectives of groundwater monitoring system in Beijing plain

During long-term monitoring, firstly, we can not only characterize the groundwater system but also analyze groundwater quantity.

Secondly, the changes of recharge, storage and discharge can be monitored, the effect of groundwater to the climate also important, which we can get from these data. And calibrate the model of groundwater flow.

Last but not least, these data can also be connected with the country water resources management. Such as assess the impact of groundwater change and set up the protection measures by the results of monitoring.

1.4 Measuring details in Beijing Plain

Now in Beijing, there are about 650 observation wells, which is used to monitor important hydrologic parameters in a geothermal system that can indicate performance, longevity, and transient processes. 150 are professional observation wells and 500 are production wells, and most of them are located in the city.

For the professional observation wells, which are installed only in the specific aquifer to monitoring groundwater the technical staff will observe the wells 6 times a month, and for the production, wells are using for the irrigation and domestic water which obsess by the local residents.

During the process of monitoring the groundwater level, the measuring instruments are necessary.

(1) The measuring clock is the simplest water level monitor, suitable for water level burial

Deep observation wells;

(2) Electric induction probe, which connected to the cable marked with scale, when the electric sensor probe sends a signal (sound or light is on) when it touches the water surface, which is suitable for observation wells of various water levels;

(3) A self-counting water level gauge suspended on the water surface, which can automatically and continuously record the water level;

(4) The Pressure Transducer is suspended in the well with a cable to continuously measure the height of the water column above the pressure transducer;

(5) The acoustic probe is fixed at the wellhead area and using the parameters returned by the sound wave to continuously calculated the distance between the acoustic probe and the water.

Figure 4. A self-counting water level gauge

Figure 5. Pressure Transducer

1.5 Description of database and management

Groundwater monitoring usually started with small scale and solve the local problem, then it will transform to the monitoring of regional or the whole country.

So we separate them into two different networks. As for the small scale for the local groundwater monitoring, we call it specific monitoring network, which system has a specific purpose, such as monitoring the groundwater level of pumping well fields and detective the influence of irrigation zone. And this monitoring needs a high frequency to make sure all the changes can be discovered.

For the regional or national scale, we call it basic network system. Usually, the specific network and basic network need to be combined and informed an integrated monitoring system. And in this combination, a basic network can provide some references condition to accessing the influence of specific monitoring network.

The database establishes and management now is a weakness of Beijing plain monitoring, which need to be improved to solve not only the local problem but also can make sure get enough groundwater information of the whole country.

2. Data analysis and results

2.1 Statistical characteristics

In this part, the statistical analysis on the groundwater level of 138 observation wells which are placed at Beijing Plain in 1995 were carried out to determine the regularity of the groundwater level distribution based on statistical parameters and the created frequency histogram.

Table 1: statistical parameters of the groundwater level

Descriptive Statistics			
Mean	32.85	Kurtosis	1.66
Median	30.45	Skewness	0.999
Standard Deviation	13.12		

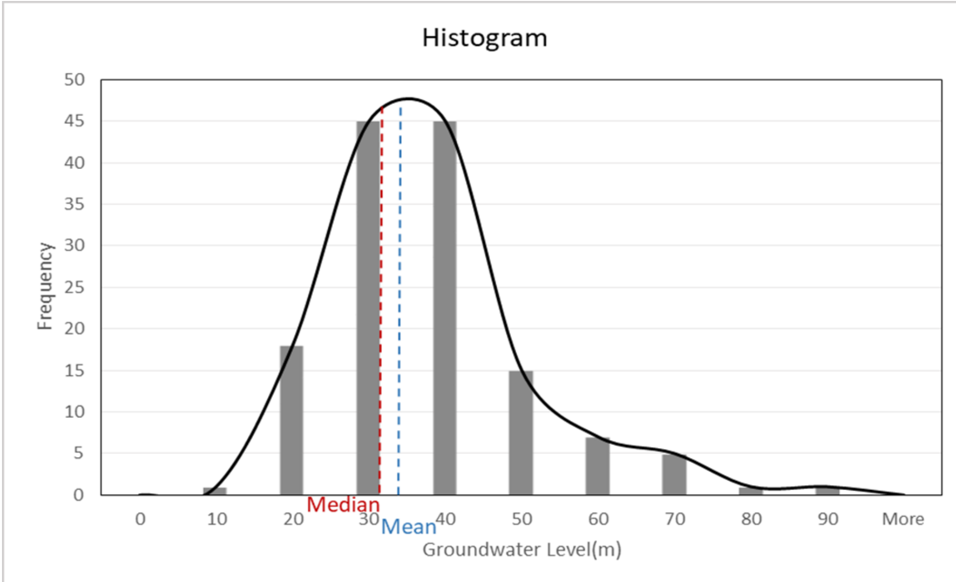


Figure 6: Relative frequency histogram of the groundwater in Beijing plain

1) Descriptors of asymmetry

From Figure 6, the shape of the histogram obviously shows asymmetric and skewed to the right due to the longer tail occurring in the right side. On the other hand, from the Table 1, statistical parameter skewness coefficient is 0.99 which is greater than 0, therefore it also presents the data set is positively skewness, indicating that most of the groundwater level gathering around 20 to 40 meters, accounting for 90% more or less of the 138 samples . Based on this, it is known that the study area is situated in the alluvial fan with good recharge, but there are a few wells showing high level at 60-90 meters because of that these wells were placed in the mountain areas with high water level.

2) Descriptors of central tendency

From the Table 1, the mean and the median value is 32.85 m and 30.45 m, respectively. The mean value is a bit larger than the median, but not much different. Hence, the mean and median values are good indicators for describing the central tendency of the groundwater level in the study area. Totally it is obtained that there is an average groundwater level at approximately 30 meters in Beijing plain.

3) Descriptors of dispersion

From the Table 1, the standard deviation is with a small value of 13.11. In the meanwhile, the relative frequency histogram is narrow from Figure 1, stating that the data set shows a small degree of dispersion from its mean value, which means that there are the majority of values are close to the average value. Therefore, in this case, it is inferred that most of the groundwater level data are around the average value, indicating they uniformly distribute spatially, does not show a huge change in space.

4) Descriptors of flatness

The Kurtosis is lower than 3, which illustrates that the distribution is flatter comparing normal distribution.

From the Figure 7, the cumulative frequency distribution shows that the groundwater level smaller than 50 meters is about 90 % among 138 observation wells. Besides, all groundwater level of 138 wells are lower than 90 meters.

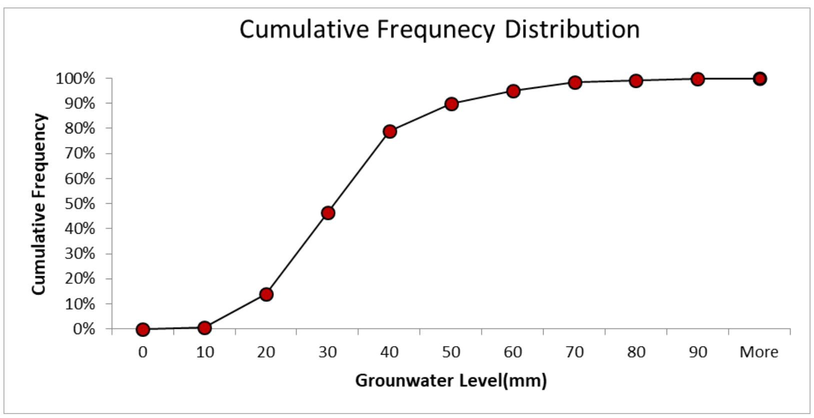


Figure 7: Cumulative frequency distribution of the groundwater level in Beijing Plain

Except statistical parameters and histogram, the third method to describe the frequency distribution is fitting probability distribution functions to empirical distributions. Because of the positive skewness of Groundwater level data, so lognormal can be used to fit the empirical distribution.

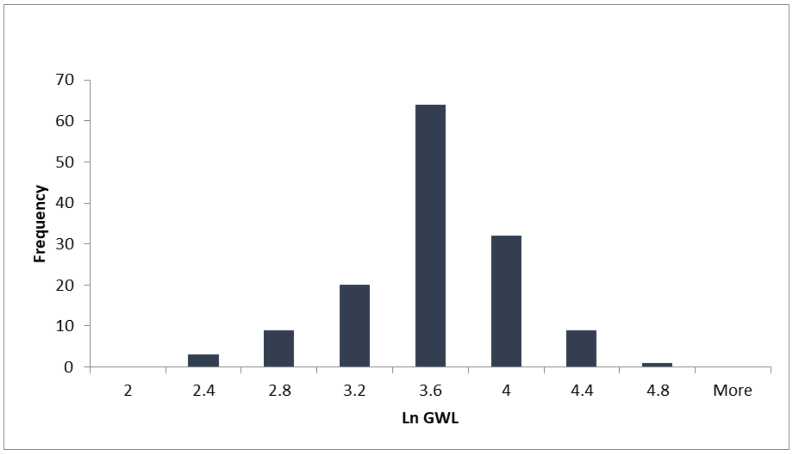


Figure 8: Histogram of logarithmic values of Groundwater level in Beijing Plain

The histogram of logarithmic values of the groundwater level shows that it is approximately symmetric about its midpoint, therefore the Logarithmic groundwater level follow the Normal distribution. Based on this, we can plot the cumulative frequency of logarithmic values of groundwater level in a logarithmic probability paper, it will show a straight line. Then the parameters like mean value and standard deviation can be found from the graph. Besides, with the known distribution function, it is easy to compute the probability of groundwater level exceeding any particular values.

2.2 Regression Analysis

Tongzhou district in Beijing Plain was chosen as the multiple regression analysis by using monthly groundwater level and precipitation at the same month, one month ago, 2 months ago until 5 months ago due to the fact that ground water level took 5 months to reach the peak after the peak precipitation. Figure 9 presents the monthly precipitation and groundwater level from 1989 to 2013. From the graph, there was an overall increase in groundwater level from 1989 to 1994 when totally yearly precipitation increasing during the same years, similarly, when the precipitation over all decreased from 1995 to 2003, the groundwater gradually decreased along this.

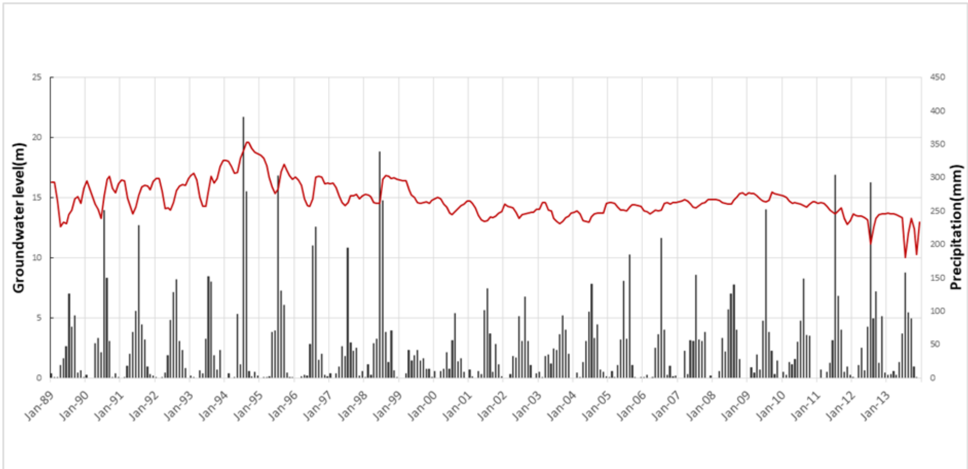


Figure 9: Groundwater level and precipitation in Tongzhou from 1989 to 2013.

From the correlation matrix (Table 2), it is known that the correlation coefficient is pretty small, but it is also clear that there is a time lag after precipitation. In addition, groundwater level has a relatively higher correlation coefficient with the precipitation occurred 5 months ago.

Table 2: the correlation matrix

	GWL	*Precipitation*	*Pt-1*	*Pt-2*	*Pt-3*	*Pt-4*	*Pt-5*
GWL	1						
Precipitation	-0.0584	1					
Pt-1	0.0964	0.4600	1				
Pt-2	0.1661	0.1445	0.4592	1			
Pt-3	0.1788	-0.1149	0.1441	0.4592	1		
Pt-4	0.1933	-0.2504	-0.1129	0.1467	0.4616	1	
Pt-5	0.2316	-0.3520	-0.2483	-0.1102	0.1494	0.4614	1

The regression equation was obtained from the correlation matrix.

$$GWL=-0.058P+0.096Pt\text{-}1+0.166Pt\text{-}2+0.179Pt\text{-}3+0.193Pt\text{-}4+0.232Pt\text{-}5 \qquad \text{(Eq.1)}$$

From the ANOVA table (Table 3) and regression statistics table (Table 4), it is known that multiple correlation coefficient R is only 0.3 and the correlation determination value is only about 0.1, showing that the goodness of fit is 10%, which indicates that the model provides a not good fit to the observed data. From the ANOVA table, the calculated F is less than Fa, so the null hypothesis is accepted, meaning that the dependent variable is not related to any of predictor variables.

Table 3: ANOVA table

	df	*SS*	*MS*	*F*	*Significance F*	*Fa(6,286)*
Regression	6	62.1339	10.3556	5.5198	1.9863E-05	2.1303
Residual	286	536.5617	1.8761			
Total	292	598.6957				

Table 4: Regression statistics

Multiple R	0.32215238
R Square	0.103782156
Adjusted R Square	0.084980383
Standard Error	1.369704366
Observations	293

On the other hand, by plotting predicated groundwater level values and actual measurement values (Figure 10), it is clear that there is not a good relationship between them.

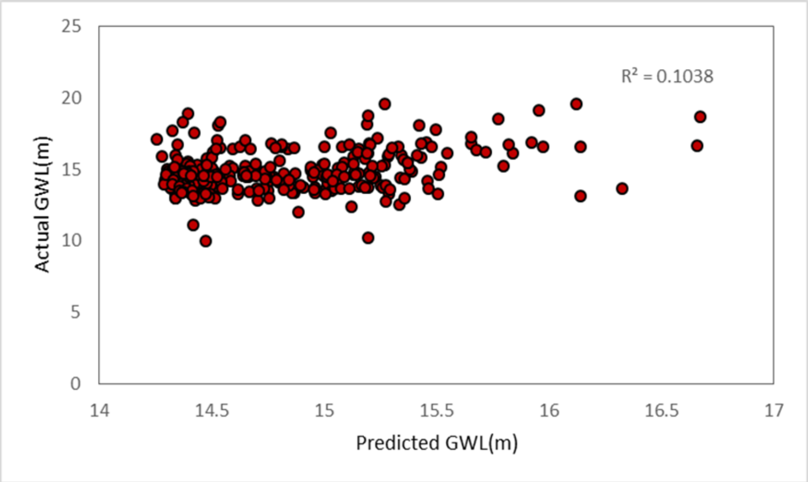


Figure 10: Predicted and actual groundwater level in Tongzhou.

As a result, the groundwater level is not directly related to the precipitation in study area Tongzhou. There are three reasons to explain this situation. Firstly, the unsaturated zone is covered with silt and clay soil type in Tongzhou district, leading to the weak infiltration into the aquifer. Secondly, the area is near the cone depression, indicating intensive human activities such as extraction influence on the groundwater level. Lastly, the area maybe accept lateral recharge from other sources.

2.3 Time series analysis

The groundwater level time series in Tongzhou district that are selected for time series analysis are from observation well 137. The observation well 137 is an unconfined aquifer observation well and it includes 8-years' time series from 1996 to 2004.

1) Trend analysis:

The parameters of linear trend are calculated by FREQ as follows. The linear trend function is Ht = 38.0144 - 0.0276t, and the standard deviation of series is 0.686. The trend exists at a confidence level of 95%, because the calculated t-value 160 is larger than the t-alpha 2 which is from the Stuednt's table. Figure 11 indicates a clearly sharp downward trend in Well 137 with a dropping level of 14 meters from 1996 to 2004.

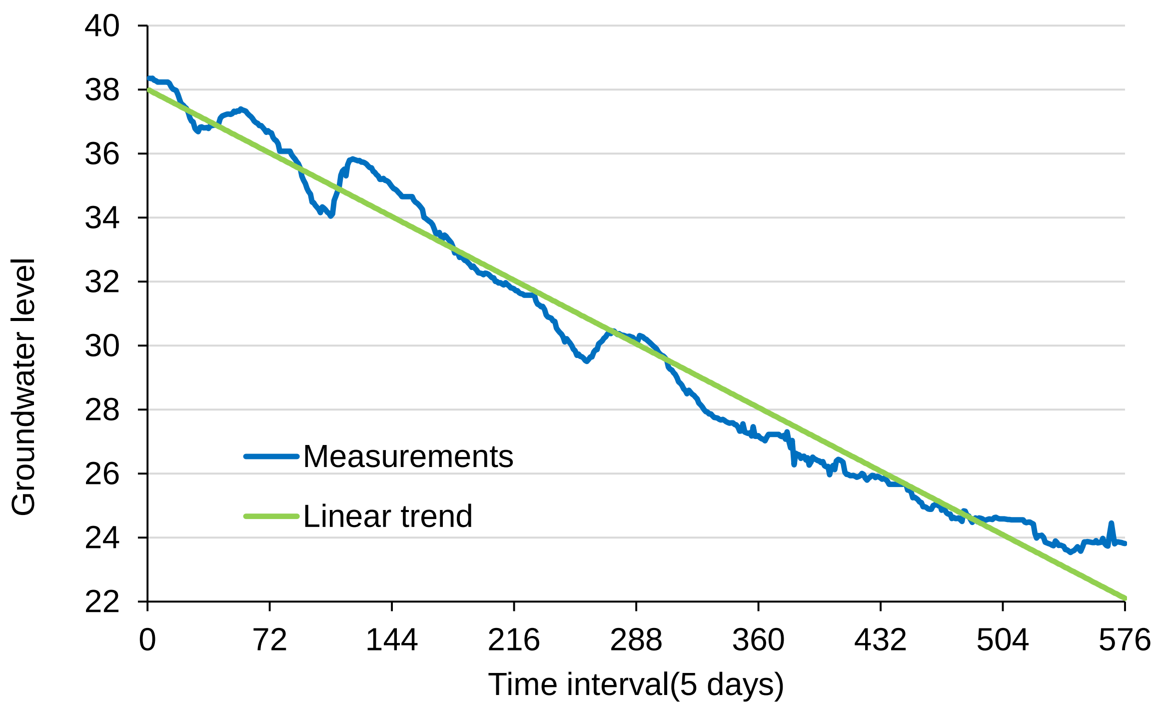


Figure 11 Groundwater level time series and fitted linear trend in Well 137

2) Periodic fluctuations

The differences between the groundwater time series and the trend line show the periodic fluctuation. The Harmonic series are used to fit the series period fluctuation. Table 5 lists the results. It can be observed the dominant periodic fluctuation is 8 years period, which is the total time series period. And choosing the first five period to estimate the period fluctuations, the estimated line compared with time series draws on Figure 12. The main five period is larger than one year, which means long periodic cycle exists in Beijing Plain and will be considered in the forward frequency optimization analysis. Another analysis from Figure 12 is that the groundwater table data series with the trend removed usually have seasonal changes. This is due to the influence of precipitation and extraction.

Table 5 Results of periodic analysis of groundwater level series in Well 137

J	**Periods**	**SIG**	**SIG/SUM**	**A(J)**	**B(J)**
0	0			0	
1	576	0.2183	0.4655	0.6007	0.2753
2	72	0.0605	0.5944	0.3377	-0.083
3	82.2857	0.0368	0.6728	-0.0788	-0.2595
4	144	0.0368	0.7513	0.2712	-0.001
5	192	0.036	0.828	0.0075	-0.2682

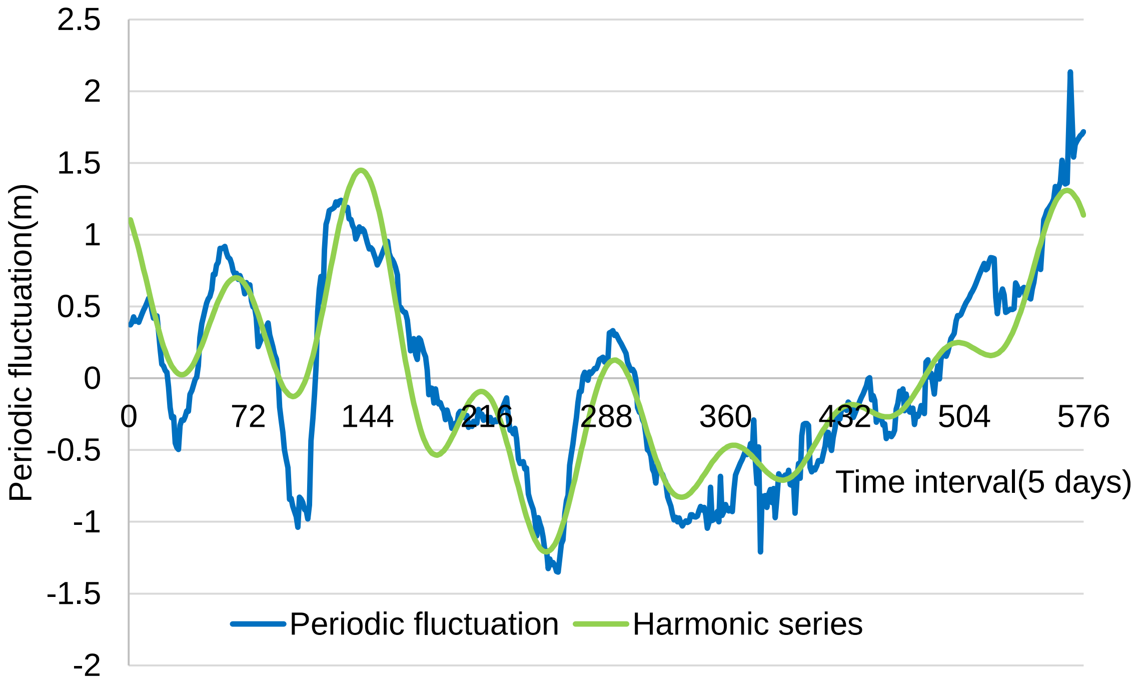


Figure 12. Fit for harmonics to groundwater levels in Well 137

3) Autoregressive analysis

After subtracting the trend and period of the groundwater time series data, the left components are stationary and the autoregressive model is used to analyze the autocorrelation characteristics of the stationary series. The analysis shows that the stationary series can be simulated with the AR (1) model. The AR (1) model fits well with the actual sequence. The fit of the AR(1) model is shown in Figure 13 for observation well 137. The residuals are almost random and independent (Figure 14). The reason of some values of correlation are out of limitations maybe the residual of the periodic component. The estimation of period fluctuation is not completely fit for the measured series, this may result in the remaining component is not totally stochastic.

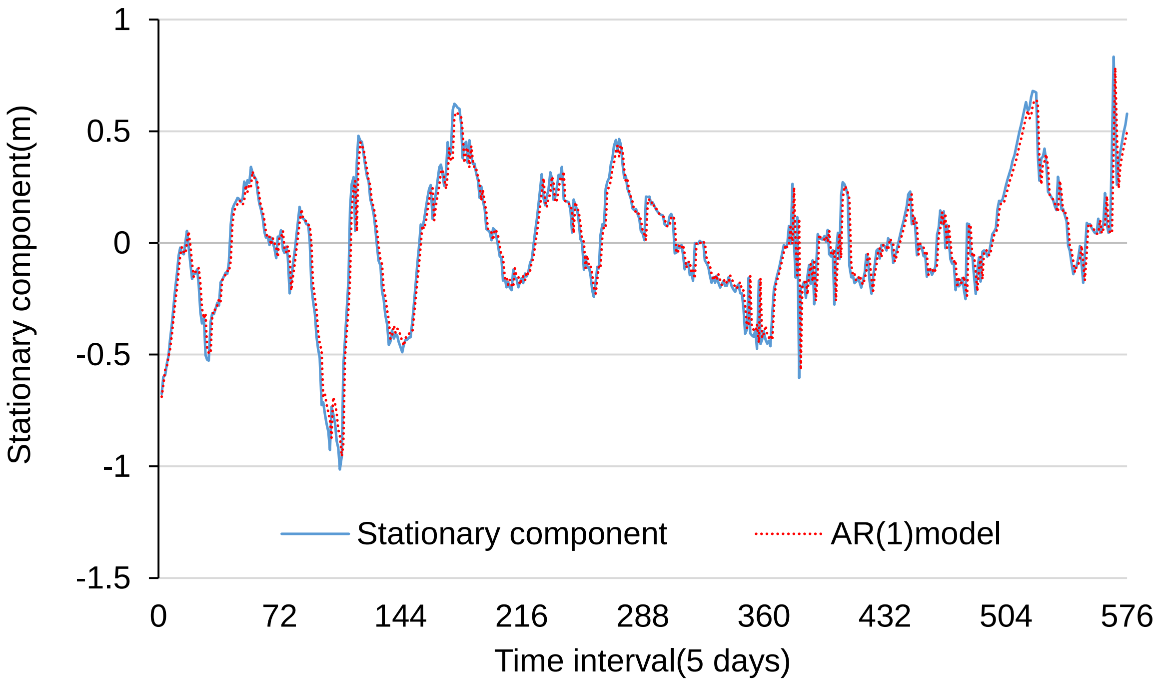


Figure 13. Fit of AR (1) model to the stationary component

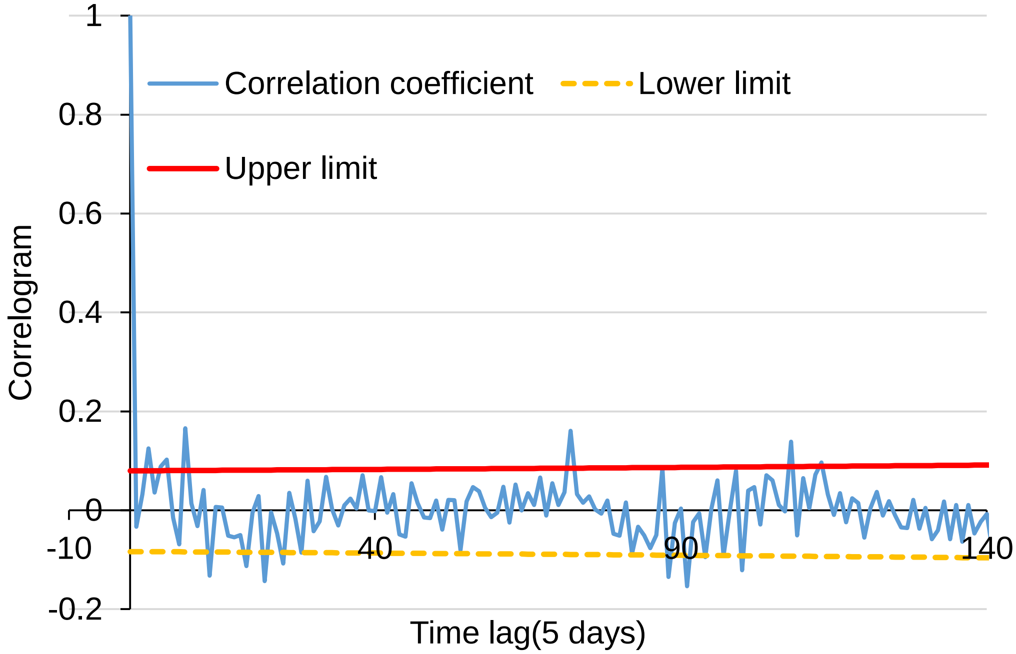


Figure 14. Correlogram of residuals

2.4 Spatial analysis

In the spatial analysis of Beijing Plain, the water level data of all the unconfined aquifer observation wells in one day are used in the Kriging method. Figure 15 shows the spatial distribution of observation wells of unconfined aquifer.

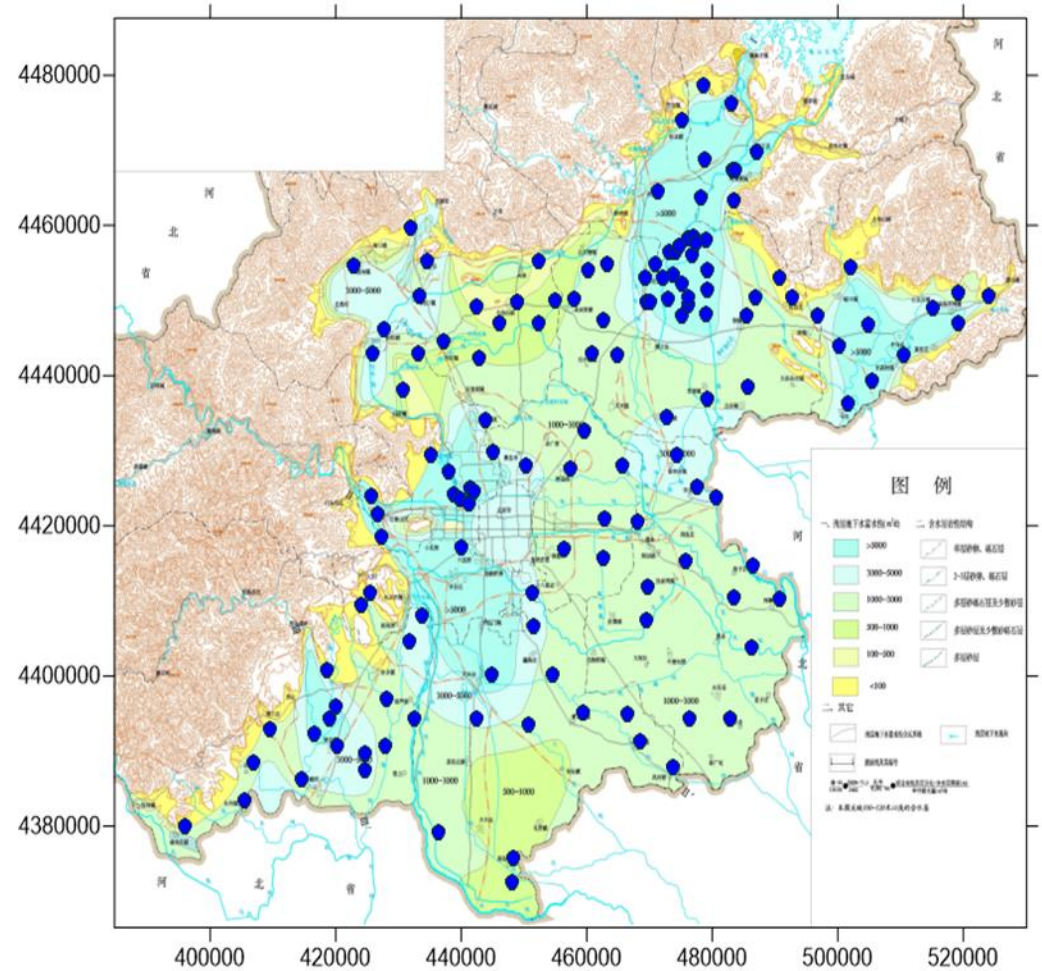
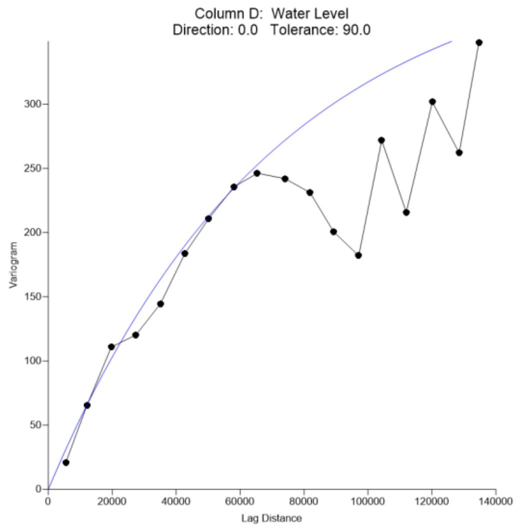


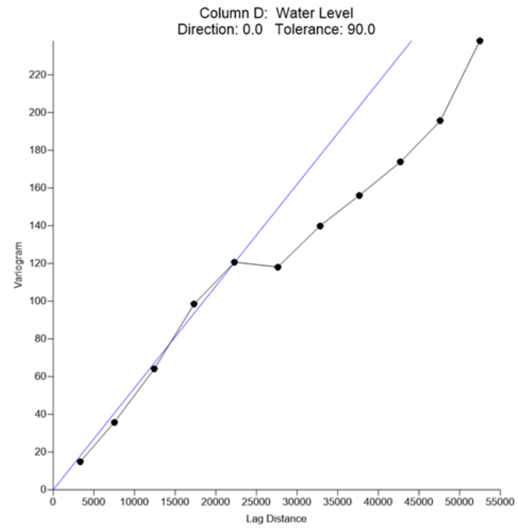
Figure 15. Locations of observation wells of unconfined aquifer in Beijing Plain

1) Fit of variograms

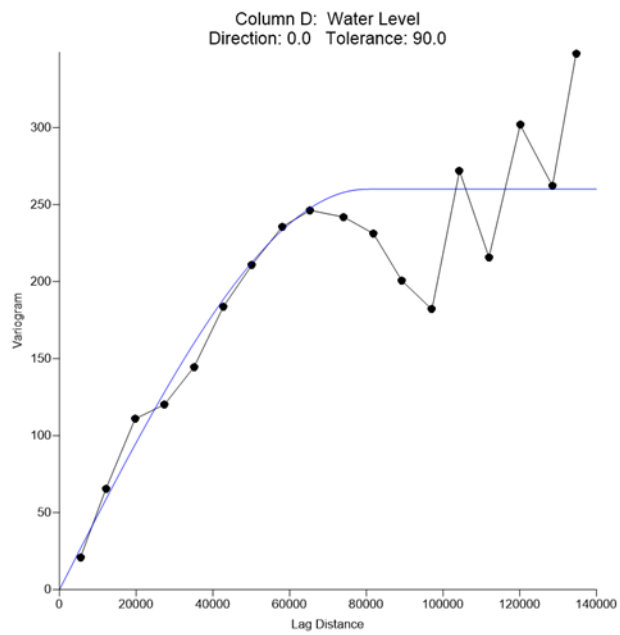
In this group case study, we use three different variograms model, exponential model, linear model and spherical model to fit. The fits of three variograms models are shown in Figure 16 and the three histograms of residuals are shown in Figure 17 as follows.



a) Exponential model



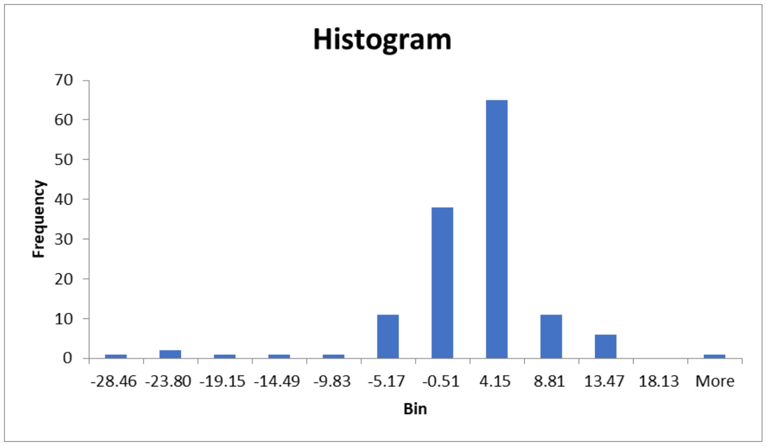
b) Linear model



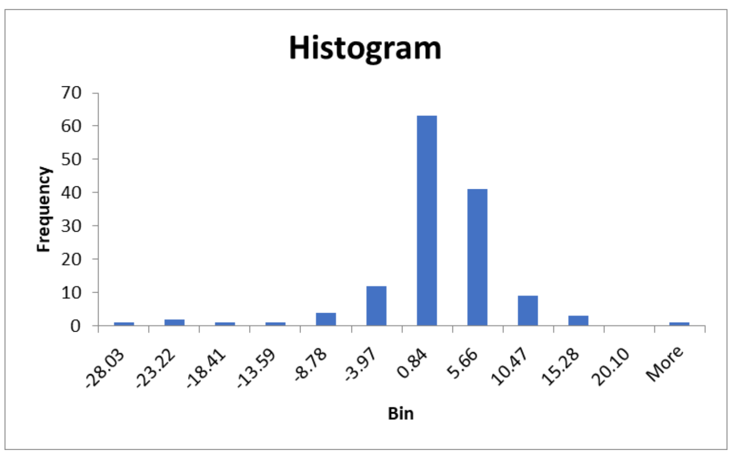
c) Spherical model

Figure 16. The fits of three variograms for water level values

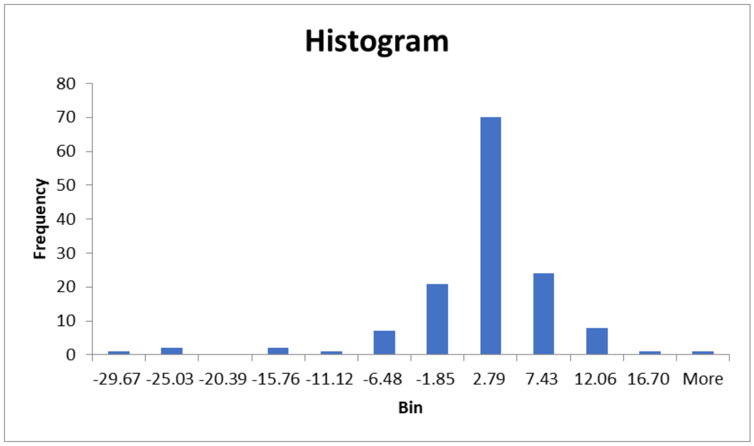
The fitness of three variograms in Figure 16 are similar. For all three variograms the fit at beginning part of lag distance is very good, while at the part of larger lag distance the performance of spherical model is better than the others, which we can also get by comparing the histograms of residuals. The spherical model is the only one model which histogram of residuals is normal distribution. The cross validation (not shown in this report) also indicates the good performance of three variograms models by calculating the mean error is near zero. However, the ratio of estimation error variance to Kriging variance is much larger than, which is the indication of errors in the larger lag distance.



a) Exponential model



b) Linear model

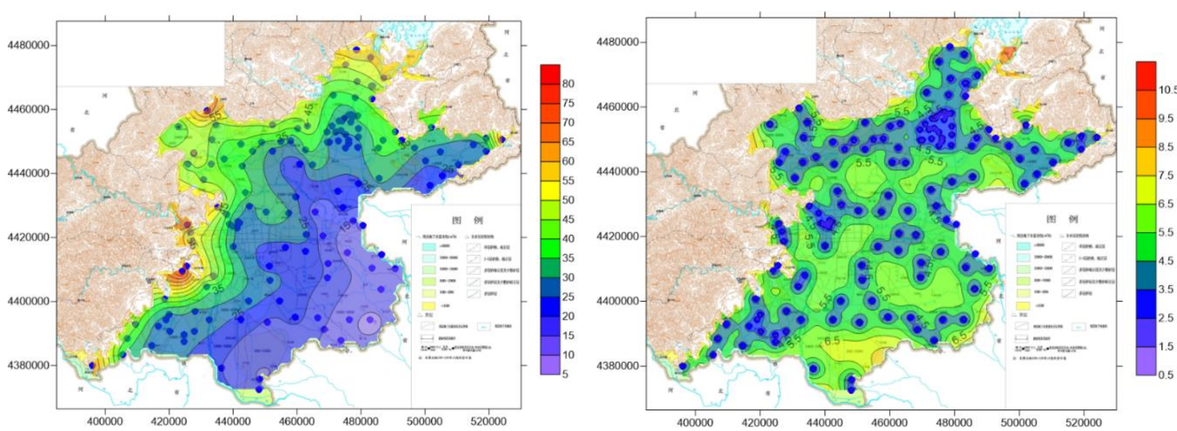


c) Spherical model

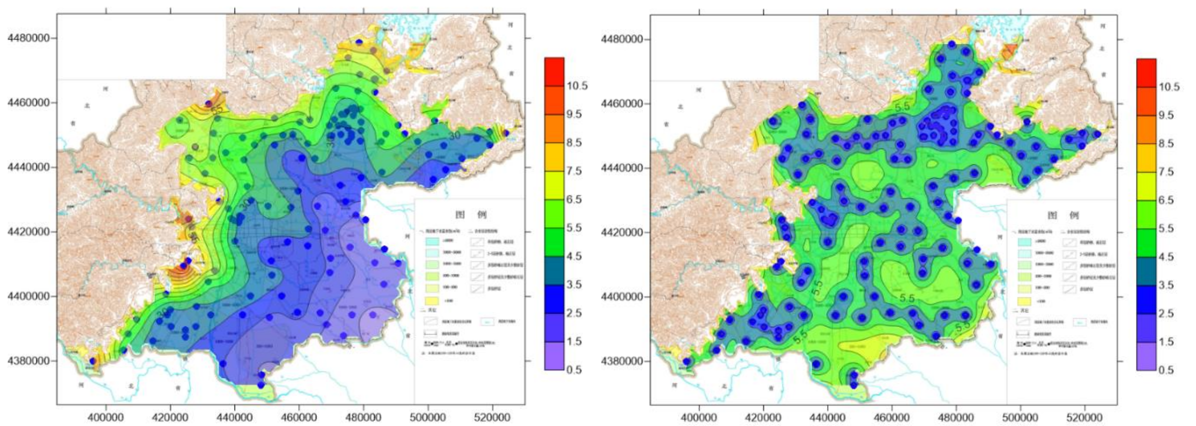
Figure 17. Histogram of residuals

2) Kriging estimation

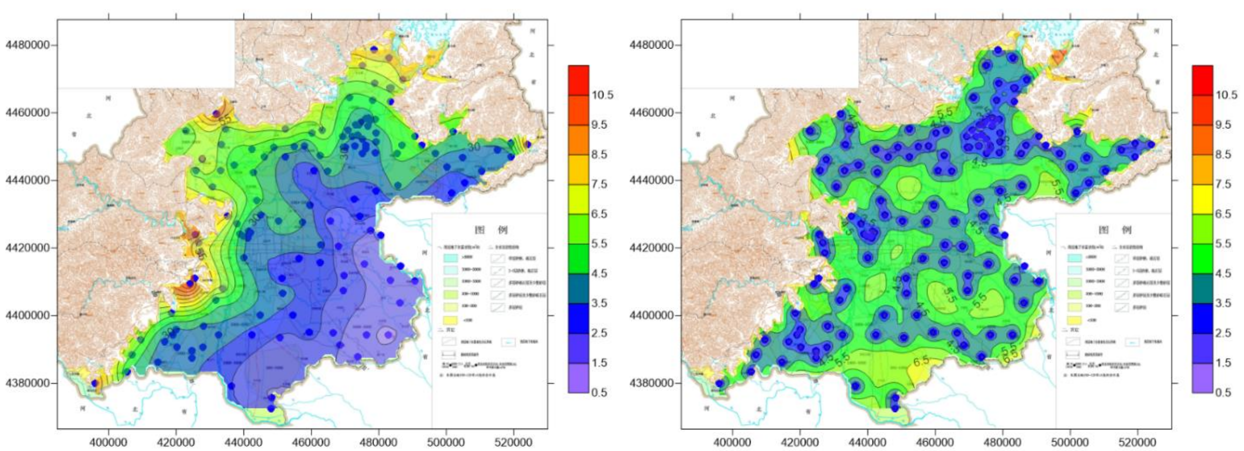
Because the goodness of fit for three variograms is similar, we choose to use all the three variograms to estimate the water level values at the locations where there are no measurements. Figure 18 shows the contour map of water levels and Kriging Standard Deviation in Beijing Plain. The results of three different models are similar. This is consistent with the results of fit of variograms and the histogram of residuals.



a) Exponential model



b) Linear model



c) Spherical model

Figure 18. Contour maps of estimates of water level and estimation KSD for water level

The contour maps of estimates of water level can indicates that the water level is higher in the northwest of Beijing Plain and lower in the southeast, which is consistent with the topological condition. And we can indicate that there are some area in the middle of Beijing over abstracting groundwater. From the contour maps of Kriging Standard Deviation locations which are lack in observation wells are determined.

3 Optimization of the monitoring network

There are two brunches of optimizing the monitoring network, one is optimization of spatial distribution of monitoring sites, and another one is optimization of frequency. The optimization of spatial distribution is completed by the approach of Kriging, and the optimization of frequency is based on the time series analysis.

3.1 Spatial distribution of monitoring sites optimization

The Kriging Standard Deviation can explain the error between estimated values between actual values. Thus, the contour map of KSD can indicate the zones which are lack of observation wells. From Figure 19, the contour map of KSD before optimization, two categories area short of observation wells is determined. The first one is the mountain front recharge area, and the other one is the zones of no observation wells. Therefore, in the optimization approach, some new water level monitoring sites should be built in these area. Meantime, there are some additional observation wells in Beijing Plain, which are too crowed and not necessary to exist. These monitoring sites also should be canceled after the optimization. The contour map of KSD after optimization is in Figure 20. Compared with the two contour maps before and after optimization, the values of KSD decline obviously. The most Kriging Standard Deviation after optimization is lower than 5, while this value is larger than 5 in many parts of study area before optimization.

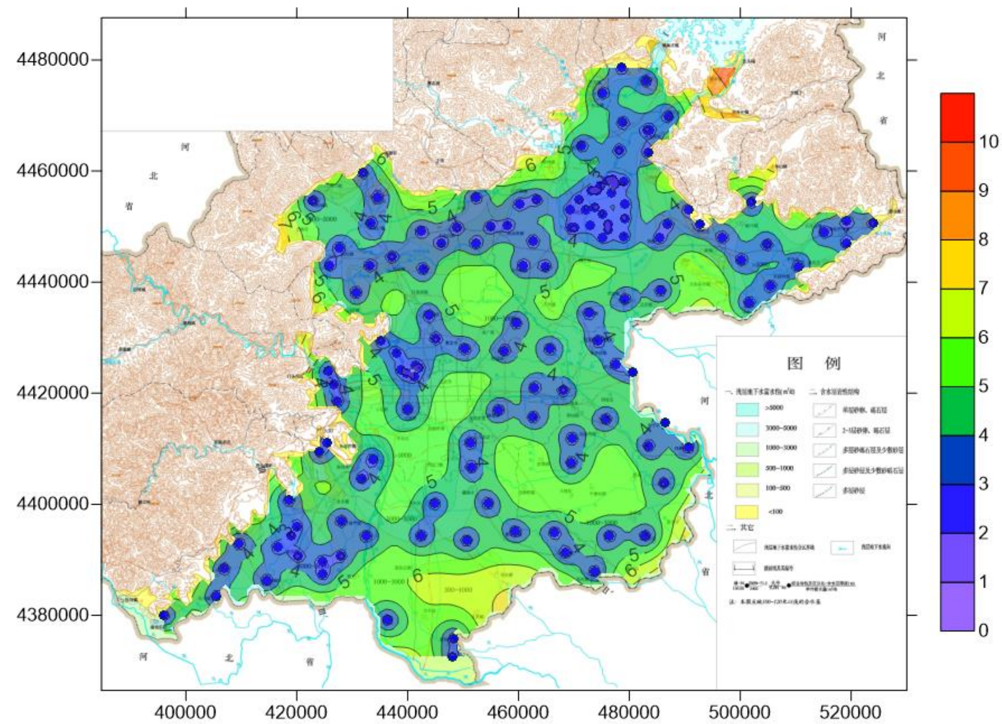


Figure 19. Contour map of KSD before optimization in Beijing Plain

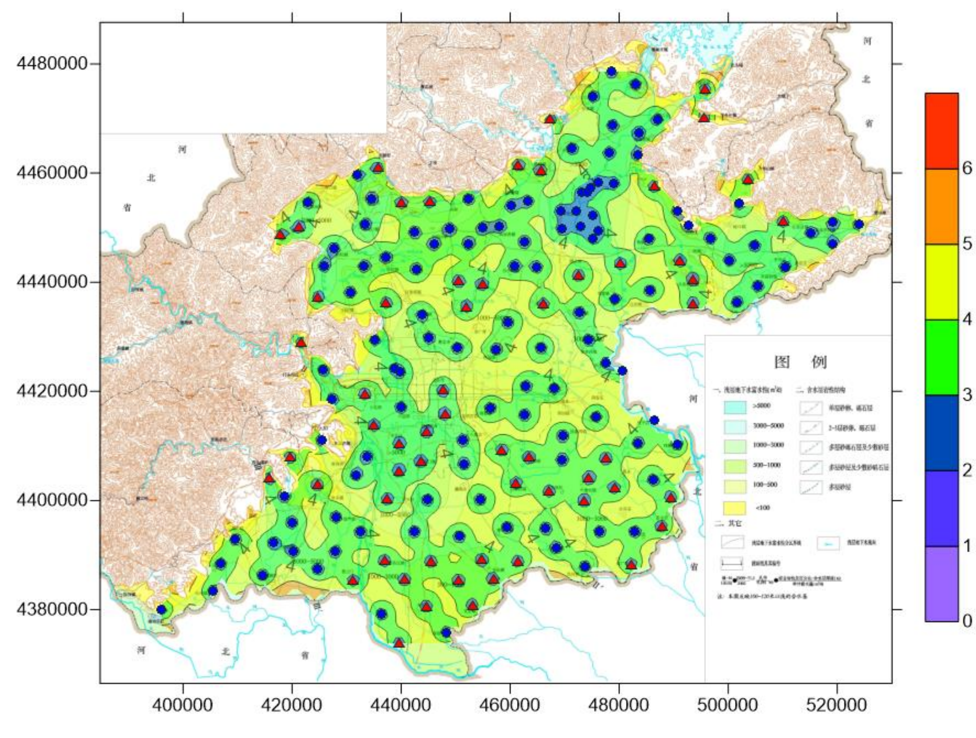


Figure 20. Contour map of KSD after optimization in Beijing Plain

3.2 Frequency optimization

In the session 2.3 time series analysis, we indicate that the groundwater level series consist of three main components, trend, period fluctuation, and a stationary component. Thus the objective of frequency optimization is that we can determine the trend, period using a specific time series. The length of the time period in which a trend and a cycle should be detected is assumed to two years (144 periods in this study). And the confidence level is set as 0.05. The analysis results are in Figure 21 and 22 as follows.

When sampling frequency is larger than 0.1, the power of trend detection and half-width is equal to the constant. So the minimum of sampling frequency is 8 times per year. However the original frequency is six times per month, it is too much often. Thus, based on the results of analysis, we change the frequency from six times per month to once per month. Meantime, for getting more details the auto monitoring instruments are recommended to set up at the sites of observation wells.

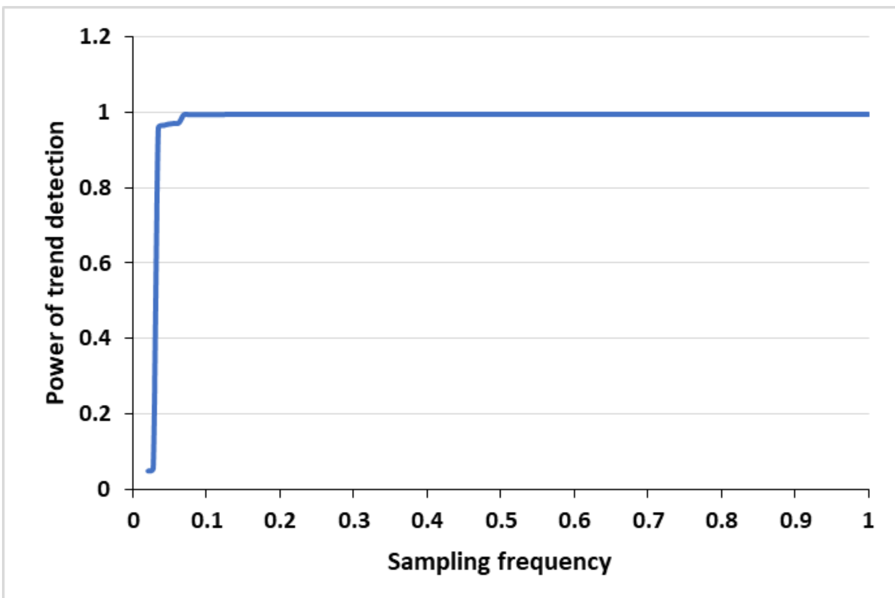


Figure 21. Power curves of trend detection versus sampling frequency

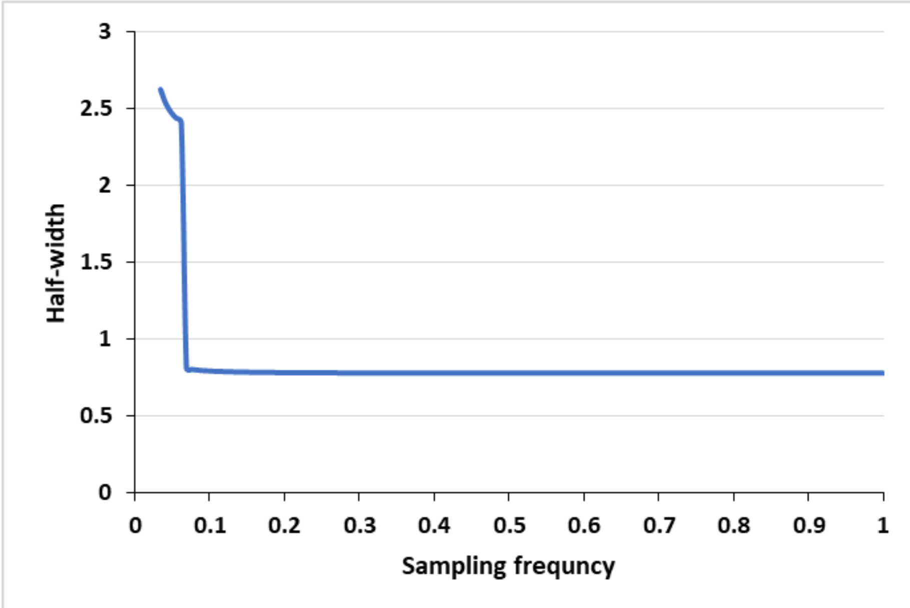


Figure 22. Half-width versus sampling frequency

4 Conclusions and recommendations

The monitoring system of groundwater level in Beijing Plain is historical and conducts series of creditable data. While the database and information management is the weakness of Beijing Plain groundwater level monitoring system. Using Kriging interpolation method analyze the rationality of monitoring wells space distribution. After optimization we add 60 new wells in Beijing Plain and delete 22 old wells. Time series analysis shows that the groundwater level in the Beijing Plain generally has a continuous downward trend and annual cycle changes. Frequency optimization indicates that these large time scale changes can be detected by monthly water level monitoring instead of six times measuring in past time. The groundwater monitoring system is lack of the electrical database, model and open source about groundwater information to the public. The recommendation is that the government should build some models and information websites for publics and water using department, like what has been built in the Netherlands.

5 References

Observation Wells | Open Energy Information. (2020). Retrieved 16 April 2020, from https://openei.org/wiki/Observation_Wells

Zhou, Y., et al. (2013). "Upgrading a regional groundwater level monitoring network for Beijing Plain, China." Geoscience Frontiers 4(1): 127-138.

Zhou, Y (2009). Hydrogeostatistics. 3rd ed. Delft: UNESCO-IHE, Institute for Water Education.

Zhou, Y (2009). Groundwater Monitoring. 3rd ed. Delft: UNESCO-IHE, Institute for Water Education.

Jousma, G., Roelofsen, F.J., (2004). World-wide Inventory on Groundwater Monitoring.

International Groundwater Resources Assessment Centre, TNO, Utrecht, the Netherlands

Heath, R.C., (1976). Design of groundwater level observation well programs. Ground Water 14 (2), 71e77.

UNESCO, (1998). Monitoring for Groundwater Management in (Semi-) arid Regions. UNESCO, Paris, France.

WMO, (1989). Management of groundwater observation programmes. In: Operational Hydrology Report No. 31. WMO, Geneva, Switzerland.

Distribution of the work in our group：

1. Review: Weijia Luo and Feiran Wang.
2. Data analysis:

   2.1 Statistical characteristics: Yining Zang

   2.2 Regression analysis: Yining Zang

   2.3 Time sires analysis: Zhechen Zhang & Zhuowei Quan

   2.4 Spatial analysis: Zhechen Zhang
3. Optimization: Zhechen Zhang & Feiran Wang