Study on Prediction Model of Karstic Large Spring Water Level Dynamic Coupling Multiple Factors in Jinan

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Abstract: In karst regions, due to the heterogeneous features of karst medium, the characteristics of the groundwater flow turn to be of high complexity. Researchers have been seeking proper forecasting methods for karst water dynamic for many years. This paper, taking the spring in Jinan as an example, using regression analysis, analyzed the factors influencing spring water dynamic, and quantitatively evaluated the influencing coefficients of spring water level concerning rainfall, exploitation and recharge as well as the natural decay coefficient of spring water in dry seasons. The prediction model coupling multiple factors was built by investigating natural and anthropogenic factors influencing groundwater level, which could be used for forecasting dynamic of spring water in Jinan. The calculated value of model was highly coincided with the observed value. In consideration of the characteristics of uneven precipitation in Jinan, the suitable zones and volume of artificial recharge were investigated finally, which could help to sustain the spewing of Jinan springs significantly.

Keyword: Coupling model, large karst spring, water level dynamic, artificial recharge

1. INTRODUCTION

Karst water dynamic is the comprehensive reaction of both geological environmental conditions and forming conditions of water resource. The human activities strengthened the complexity and forecasting difficulty of groundwater dynamics. Previous researchers made large efforts on models for predicting groundwater table, such as regression analysis model, frequency spectrum analysis method, time series model, grey system prediction method, fuzzy prediction method, artificial nerve network method, wavelet analysis method and so on [1-10], as well as prediction model of water level based on the software of numerical simulation [11, 12]. There are lots of methods being widely studied, even put into application, and good precision and applying value are proved in these research papers. However, there are lots of disadvantages, such as low precision, lacking physical significance, multiple solutions and so on, needing constantly to be improved.

Jinan is famous for spring which played an important role in economy and culture. Under natural conditions, Baotu spring is a perennial spring. With the social development, more and more groundwater got extracted, especially between 1970s and 1990s, which has led that Baotu spring had dried up several times from 1972 to 2003. In order to recover the spring, the conservative measure like shutting down water supply had been taken in early period of this century until the spring recovered flowing in September 2003 [13]. At present, although the groundwater exploitation decreased largely, there still existed a large problem that spring would still stop flowing in dry seasons, which has not been fundamentally solved. The main reasons are that the hydrogeological conditions are complicated and variable regulations of groundwater dynamics are not grasped effectively. The groundwater level is effected by natural and anthropogenic factors [14], such as meteorology, hydrology, geology, artificial exploitation, recharge, city expansion, ground surface hardening and so on. Based on 40 years’ data of groundwater dynamics, this paper analyzed the factors influencing groundwater dynamics, which showed that the anthropogenic influence on groundwater level changed vastly among different historical periods. Therefore, the multiple factors coupling prediction model got established in order to explore forecasting methods of large karst spring dynamics.

2. HYDROGEOLOGICAL BACKGROUND

Jinan spring field is located in the north edge of Luzhong mountainous region, and gradually gets lowered topographically in elevation from the south to north. In the south of the spring field, the karst water system basement, consisting of gneiss Presinian, is distributed. Respectively, in the middle of the field, the basement is covered by karstic carbonate strata of Cambrian and Ordovician inclining and emerging northward from the old to young, while the magmatic rocks, which formed in the Mesozoic Yanshan
Orogeny, are distributed in the north. In general, Jinan karst water system is a monoclinic structure. With the conditions of the above specific terrain and geological structure, after getting recharged from atmospheric precipitation in southern mountainous region, the karst water flows from south to north, which basically coincides with the dip direction of the strata and topography. When moving northward, the karst groundwater gets obstructed by impermeable Yanshanian magmatic rocks and enriched with confined karst groundwater finally flowing out as springs in the suitable areas of topography and structure (Fig. 1). The spring dynamics in Jinan got affected obviously by exploitation and climate (rainfall) (Fig. 2).

Fig. (1). Geological scheme of Jinan Springs area.

Fig. (2). The spring water level, exploitation and rainfall from 1958 to 2010.
3. ANALYSIS OF SINGLE FACTOR INFLUENCING SPRING LEVEL

According to the observation data from 1959 to 2014, the affected coefficients of different factors influencing spring level got analyzed by using regression analysis of single factor. The data, collected from water conversancy and geological department, were correct and reliable.

3.1. Influence of Rainfall on Spring Water Level

Rainfall is the main recharge source of groundwater in Jinan spring field. Therefore, analyzing rainfall features is extremely significant in groundwater level dynamic research of Jinan city. According to observation data, the relationship between spring water level and rainfall was investigated in different time scales, in order to acquire the correlation between rainfall and spring water level.

The values of annual variation of spring water level and annual rainfall during 1959–2012 were analyzed. Choosing the value of annual variation of spring water level as the dependent variable $y$, and the annual rainfall as the independent variable $x$, the scatter plot graph was drawn (Fig. 3).

As seen from Fig. (3), the correlation between the annual variation of spring water level and annual rainfall is poor. The reason is that other factors in addition to rainfall, especially large exploitation, also affect variation amplitude of groundwater level. The correlation between rainfall and spring water level is not obvious during the period of large exploitation.

$$y = 0.0033x - 0.1411$$

where $y$ (m) is variation of annual spring level, $x$ (mm) is annual rainfall.

![Fig. (3). The correlation between annual rainfall and annual variation of spring water level from 1959 to 2012.](image)

From 1959 to 1967, the average exploitation of urban zone is only $89,500$ m$^3$, and the affected degree of exploitation was equivalent. Therefore, this period of time could be selected to make regression analysis between annual variation of spring water level and annual rainfall (Fig. 4). The result showed that annual variation of spring water level and annual rainfall presented positive correlation, and the correlation coefficient ($R^2$) was 0.961. The regression equation is showed as follows:

$$y=0.0033x-2.4357$$

$$R^2 = 0.961$$

In this period, annual rainfall and annual variation of spring water level presented excellent linear trend, which showed there developed a close linear relationship between annual rainfall and annual variation of spring water level in Jinan city during the historical period when human influence was weak. That reflected there lied mathematical and physical relationship between rainfall and karst aquifer in Jinan spring area. However, since 1980s, with the increasing anthropogenic influence, the factor affecting karst aquifer of Jinan spring area has been changed. As a result, the mathematical and physical relation of the model became more complicated, which needed quantitative analysis in different aspects, such as multiple angles, multiple scales, multiple dimensions and so on. The monthly variation of spring level was selected to be researched from 2008 to 2012. Monthly rainfall ($x$) is chosen as horizontal coordinate, respectively, monthly variation of spring level ($y$) is chosen as vertical coordinate, with scatter diagram mapped (Fig. 5) and showing the linear relation between them. The equation is showed as follows, where the multiple correlation coefficient ($R^2$) is 0.6865.

Fig. (4). The correlation between annual rainfall and annual variation of spring water level from 1959 to 1967.

In this equation, $y$ (m) is served as monthly variation of water level, and $x$ (mm) is served as monthly rainfall.

$$y=0.0038x-0.1411$$

Fig. (5). The correlation between monthly rainfall and monthly variation of spring water level from 2008 to 2012.

It’s obvious that there developed well correlation between monthly rainfall and monthly variation of spring water level, which implied that a certain amount of rainfall can cause a certain amount lift of groundwater level.
However, the rainfall needs to exceed the threshold value that is an amount meeting the interception of vegetation and unsaturated zone.

The correlation between annual rainfall and annual variation of spring water level got received. The equation is showed as follows:

\[ y = 0.0033x - 2.4357 \]  \hspace{1cm} (3)

Divide the both sides of equation by 365, so equation (3) became the following:

\[ \frac{y}{365} = 0.0033 \times \frac{x}{365} - \frac{2.4357}{365} \]  \hspace{1cm} (4)

In order to unify unit as daily/(d), make a replacement:

\[ \Delta h = \frac{y}{365}, \quad P = \frac{x}{365} \]

The equation (4) turned into the following:

\[ \Delta h = 0.0033 P - 0.00667 \]  \hspace{1cm} (5)

The correlation between monthly rainfall and monthly variation of spring water level got received. The equation is showed as follows:

\[ y = 0.0038x - 0.1411 \]  \hspace{1cm} (6)

Divide both sides of equation by 30, so equation (6) became the following:

\[ \frac{y}{30} = 0.0038 \times \frac{x}{30} - \frac{0.1411}{30} \]  \hspace{1cm} (7)

In order to unify unit as daily/(d), make a replacement:

\[ \Delta h = \frac{y}{30}, \quad P = \frac{x}{30} \]

And the gotten equation (7) turned into the following:

\[ \Delta h = 0.0038 P - 0.0047 \]  \hspace{1cm} (8)

Comparing the linear equations of annual scale and monthly scale, the equation is transformed into equation of daily average variation. The equation is showed as follows.

\[
\begin{align*}
\Delta h &= 0.0033 P - 0.00667 \\
\Delta h &= 0.0038 P - 0.0047
\end{align*}
\]  \hspace{1cm} (9)

Slope values of the two above equations are respectively 0.0033 and 0.0038, with the same order of magnitude, which means the value of water level increase caused by a unit effective rainfall is 0.0033~0.0038 m, and the order of magnitude of the two constant terms (-0.0047 and -0.00667) turn to be also the same.

3.2. Influence of Exploitation on Spring Water Level

In order to analyze the influence of exploitation on spring water level, scatter diagram (Fig. 6) of average annual spring water level and exploitation is made according to the data from 1959 to 2002. This diagram implies that influencing degree of exploitation on spring water level changed because of the varied layout of groundwater exploitation wells. From 1959 to 1967, the exploitation wells were all located in urban zone and nearby the outcrops of spring. The correlation equation of this stage could be written as follows:

\[ y = -0.7146x + 37.526 \]  \hspace{1cm} (10)

where the correlation coefficient \( R^2 \) is 0.778.

The exploitation wells located in suburb far from urban zone increased from 1968 to 2002. The correlation equation became the following:

\[ y = -0.0577x + 30.155 \]  \hspace{1cm} (11)

where the correlation coefficient \( R^2 \) is 0.5019.

The equation shows there is a negative correlation between exploitation quantity and spring level. The larger the exploitation is, the lower the spring level will be. The correlation coefficient \( R^2 \) of urban exploitation to spring level could reach 0.8418, while suburb’s is 0.5019. It’s obvious that influence on spring water level in different layout of exploitation wells is different.

![Fig. (6). The relationship between the average annual spring water level and exploitation.](image)

In order to protect springs, the relevant department in Jinan City has increased the water supply from the surface water, i.e., Yellow river water, changed layout of exploitation wells and carried out artificial recharge since 2003, which has disturbed the groundwater dynamics. Scatter diagram of groundwater exploitation and spring level from 2003 to 2012 got mapped (Fig. 7).

![Fig. (7). The relationship between Springs area/10000 m³ and exploitation amount of Springs area/10000 m³.](image)

As can be seen from the Fig. (7), the correlation between groundwater exploitation and spring level is not obvious.

In order to avoid the influence of artificial recharge and exploitation layout, the period of time (from 1959 to 1967) when there only distributed urban exploitation was selected...
to analyze the influence of average daily exploitation on annual variation of spring level (Fig. 8), and the following equation got received:

\[ y = -0.5336x + 5.1281 \quad \text{(12)} \]

where the correlation coefficient \((R^2)\) is 0.8105.

Divide both sides of equation (12) by 365, then it turned into:

\[ \frac{y}{365} = -\frac{0.5336}{365}x + \frac{5.1281}{365} \quad \text{(13)} \]

In order to unify unit as daily \((/d)\), let \(\Delta h_{\text{daily}} = \frac{y}{365}, Q_{\text{daily}} = y\), so the equation changed into the following:

\[ \Delta h_{\text{daily}} = 0.00146Q_{\text{daily}} + 0.014 \quad \text{(14)} \]

The equation expressed that one daily quantity could cause the spring level decrease by 0.00146 m.

\[ \text{Fig. (8). The relationship between groundwater exploitation and variation of spring level from 1959 to 1967.} \]

3.3. Influence of Recharge on Spring Water Level

Scatter diagram about recharge amount and water level rising value in 2004, 2006 and 2008 is made (Fig. 9).

\[ y = 0.0009x - 0.0067 \quad \text{R}^2 = 0.9929 \quad \text{(15)} \]

where the correlation coefficient \((R^2)\) is 0.993, \(y\) (m) is spring water level variation, and \(x\) (m³/d) is artificial recharge amount.

In order to unify unit as daily\((/d)\), make \(\Delta h_{\text{daily}} = y\), \(R_{\text{daily}} = x\), so the equation could turn into:

\[ \Delta h_{\text{daily}} = 0.0009R_{\text{daily}} - 0.0067 \quad \text{(16)} \]

In equation (16), the oblique rate is 0.0009, which means spring water level variation caused by one daily artificial recharge amount is 0.0009 m.

4. ESTABLISHMENT AND APPLICATION OF PREDICTION MODEL

4.1. Establishment of Prediction Model

Firstly, the initial water level is set as \(H_0\). After \(\Delta t\) days, the water level changed, and the final level value is the algebraic sum of the initial water level \((H_0)\) and spring water level variation\((\Delta h)\) of this period. The equation can be written as follows:

\[ H = H_0 + \Delta h \quad \text{(17)} \]

where \(H_0\) is the initial water level, and \(\Delta h\) is the spring water level variation after \(\Delta t\) days.

Combining the former equations of (8), (14) and (16), equation (18) was obtained.

\[ \text{rainfall:} \quad \Delta h_{\text{daily}} = 0.0038P_{\text{daily}} - 0.0047 \]

\[ \text{Exploitation:} \quad \Delta h_{\text{daily}} = -0.00146Q_{\text{daily}} + 0.014 \quad \text{(18)} \]

\[ \text{recharge:} \quad \Delta h_{\text{daily}} = 0.0009R_{\text{daily}} - 0.0067 \]

Then,

\[ \Delta h_{\text{daily (PQR)}} = (0.0038P_{\text{daily}} - 0.0047) + (-0.00146Q_{\text{daily}} + 0.014) + (0.0009R_{\text{daily}} - 0.0067) \quad \text{(19)} \]

\[ \Delta h_{\text{daily (PQR)}} = 0.0038P_{\text{daily}} - 0.00146Q_{\text{daily}} + 0.0009R_{\text{daily}} + 0.0026 \quad \text{(20)} \]

After \(\Delta t\) days, the total spring water level variation caused by rainfall, exploitation and artificial recharge turned to be as follows:

\[ \Delta h_{\text{(PQR)}} = 0.0038 \sum_{i=1}^{\Delta t} P_i - 0.00146 \sum_{i=1}^{\Delta t} Q_i + 0.0009 \sum_{i=1}^{\Delta t} R_i + 0.0026 \quad \text{(21)} \]

According to the analysis of spring water dynamic curve, it has found that with the natural discharge, groundwater level presented a natural decay value being acted as \(\lambda_D\), varying from 0.0078 to 0.0082 m/d. Therefore, after \(\Delta t\) days, natural variation could be showed as follows:

\[ \Delta h_N = \lambda_D \Delta t \quad \text{(22)} \]

The prediction model coupling multiple factors fit for Baotu spring of Jinan are obtained.
\[ H = H_0 + \lambda_D \Delta t + 0.0038 \sum_{i=1}^{\Delta} P_i - 0.00146 \sum_{i=1}^{\Delta} Q_i + 0.0009 \sum_{i=1}^{\Delta} R_i + 0.0026 \]  

(23)

According to the above analysis and correlation equations expressing the influences of rainfall, exploitation, and recharge amount on spring water level variation, each influencing coefficient was extracted as follows: the influencing coefficient of effective rainfall signified as \( \lambda_R \) is 0.0038 m/mm. The decrease value of spring water level caused by exploitation is affected by layout of exploited wells, the influencing coefficient of exploitation was different because of different locations of exploited wells, which can be signified as \( \lambda\), and \( \lambda_R = (\lambda_{Q1}, \lambda_{Q2}, \lambda_{Q3}, \ldots) \). Respectively, the influencing coefficient of artificial recharge on spring water level was affected by locations of recharging, which can be signified as \( \lambda_R \), and \( \lambda_R = (\lambda_{R1}, \lambda_{R2}, \lambda_{R3}, \ldots) \). \( \lambda_D \) was used to represent the natural decay value of groundwater level.

According to the above analysis, an equation is obtained as follows:

\[ H = H_0 + \lambda_D T - \lambda_Q Q + \lambda_R R + \lambda_P P + C \]  

(24)

In the equation (24), \( T = \sum_{i=1}^{T} 1 \) serves as the natural decay function, and its unit is d;

\( R( R = \sum_{j=1}^{T} R_j ) \) serves as recharge function, and its unit is 10,000 m\(^3\);

\( Q( Q = \sum_{j=1}^{T} Q_j ) \) is exploitation function, and the unit is 10,000 m\(^3\);

\( P( P = \sum_{j=1}^{T} P_j ) \) is rainfall function, and unit is mm; \( C \) is constant value.

Therefore, in different period of time, the forecasting equation of spring water level got attained as follows:

\[ H_i = H_0 - \lambda_D \sum_{j=1}^{t} 1 + \lambda_R \sum_{j=1}^{t} P_j + \sum_{j=1}^{t} \lambda_Q \sum_{j=1}^{t} Q_j + \sum_{j=1}^{t} \lambda_R \sum_{j=1}^{t} R_j + C \]  

(25)

\( t, j, i, m, n \geq 1, \text{being positive integer; } Q_j, R_n, P_j \geq 0 \)

4.2. Reliability Analysis of Model

Using the established regression model, complemented with measured data of exploitation, rainfall and recharge amount from 2004 to 2014, the water level of Baotu spring got calculated, and then compared with the measured water level to make reliable analysis. Fig. (10) shows the forecasted result.

Fig. (10). Time-series graph of calculated and observed Baotu spring water level from 2004 to 2014.

Fig. (11) implies that the curve of calculated value and the curve of observed value of Baotu spring water level are extremely closed and similar. In Fig. (11), there shows 4018 samples, and the correlation coefficient (R\(^2\)) is 0.9071, the mean absolute error is 0.1516 m, as well as the standard prediction error is 0.0066. The above implies that the calculated value is of high precision, and can be used to predict the spring water level in the future.

Fig. (11). Calculated value versus observed value of Baotu spring water level.

This model uses the rainfall, exploitation and recharge amount as the main variables to predict spring water level, and the precision is day. If adopting different combination of rainfall, exploitation and recharge amount, the spring water level under different situations can be forecasted (Table 1).

4.3. Prediction of Spring Water Level Dynamic

Water level observation of about 30 years shows that the time of stopping flowing of Jinan spring all is in dry seasons from April to June. For protecting the famous springs, the goal of forecasting Baotu spring water level in dry season from January to June, 2015 gets set. The initial water level (\( H_0 \)) is elevation value of groundwater level on January 1, 2015. Exploitation and recharge amount adopt designed value. Rainfall amount of different forecasting period is distributed according to monthly rainfall ratio (Table 2). The designed value of rainfall probability is 25%, 50%, 90% (Fig. 12).
Table 1. Chart of statistical analysis.

<table>
<thead>
<tr>
<th>Sample Size (N)</th>
<th>Mean Error (ME)</th>
<th>Mean Absolute Error (MAE)</th>
<th>Mean Absolute Relative Error (MARE)</th>
<th>Standard Deviation of Forecast Errors</th>
<th>Correlation Coefficient R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>4018</td>
<td>-0.0943</td>
<td>0.1516</td>
<td>0.0053</td>
<td>0.0066</td>
<td>0.9071</td>
</tr>
</tbody>
</table>

Table 2. The monthly distributed ratio of multiple years’ statistical rainfall amount.

<table>
<thead>
<tr>
<th>Month</th>
<th>Rainfall ratio (%)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.26</td>
<td>1.58</td>
<td>1.3</td>
<td>4.31</td>
<td>10.28</td>
<td>9.96</td>
<td>29.44</td>
<td>28.13</td>
<td>10.48</td>
<td>2.3</td>
<td>1.32</td>
<td>0.64</td>
</tr>
</tbody>
</table>

According to the model calculation, the predicted results (Fig. 13) of Baotu spring water level show that under rainfall probability of 90%, Baotu spring water level will decrease below the elevation value of Baotu spring. On May 30, 2015, Baotu spring will stop flowing. Therefore, the emergency recharge measures of protecting spring should be taken to ensure that the large karst spring would not stop flowing.

Fig. (12). The designed value of rainfall amount from January to June, 2015.

Fig. (13). Time-series graph of calculated and observed Baotu spring water level.

4.4. Feasibility Analysis of Recharge

In order to study the groundwater flow paths after artificial recharge, tracer test in Quanlu seepage zone was carried out from June to December, 2014. The tracer detection range is shown in Fig. (14). According to the tracer test, groundwater flow field and drilling data, it is concluded that groundwater hydrodynamic field characteristics of Jinan karst water system mainly has three points:

- Fracture-karst development is of heterogeneity, including tubular, karst cave, cracks and so on. The degree of karst development differs among different lithology, and even in the same lithology, the degree also changes because of different tectonic position. Therefore, the apparent groundwater velocity is different.
- Along the tectonic fracture zone and influence zone of fracture fissure, the favorable pathway for groundwater migrating is formed, where the apparent groundwater velocity is fast. Structural belt is the ideal source location.
- Because of tectonic fracture zone presenting well hydraulic conductivity, there develops a favorable hydraulic connection between Zhangxia formation limestone aquifer of Cambrian and Ordovician limestone aquifer. Therefore, recharging groundwater in Zhangxia limestone of Cambrian would have a well effect on spring protection. Meanwhile, it also shows the correctness of the research range of the numerical model.

4.5. Determination of Recharge Amount

In the equation (2), the linear relation shows that a certain amount of rainfall can cause a certain amount of rise of groundwater level. However, if the rainfall is very little, it is called ineffective rainfall. Therefore, there is a rainfall threshold value causing the rise of groundwater level.

Intersection point of linear equation and x axis is 37.13mm, which is the rainfall threshold value under the monthly scale (Fig. 5). If monthly rainfall in dry seasons is less than 37.13mm, the artificial recharge will be necessary to keep spring water steady. Converting from 37.13 mm rainfall, the recharge amount of groundwater is 290,000 m³/d, which means that the recharge amount should be 290,000 m³/d to keep spring water steady. 37.13 mm rainfall which is a threshold value under monthly scale is different from the threshold value of water level rise caused by single rainfall. Previous researchers studied the threshold value of rainfall of water level rise caused secondary rainfall under different rainfall intensity in limestone region. This value is also not
valid for different development extent of karst and different thickness of unsaturated zone as the test is in the small area, and this value has a certain limitation concerning practical application of large region engineering.

5. SUMMARY

- Based on the principle of superposition, the prediction model is put forward concerning groundwater dynamic of large karst spring in North China. According to the application of Baotu spring water level of Jinan city, the calculated value is highly fitting for observed data. Estimated prediction model has high precision and practical applied value.

- This prediction model not only considers factors such as rainfall, artificial exploitation, artificial recharge and so on, more importantly, but also brings in the flux decay factor of spring aiming at the specialty of large karst spring, so as to achieve the coupling between natural factors and anthropogenic influence. The prediction model is of certain theoretical significance.

- In consideration of uneven rainfall in time and space, the ground water level decreases during dry seasons, and thus spring discharge attenuation is nature. To avoid spring cutoff in dry seasons, the implementation of artificial recharge is necessary. In order to select recharge area, specific hydrogeological conditions should be considered. Recharge volume is calculated to be 290 000 m³/d.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.
