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

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Abstract: In karst region, due to the heterogeneous features of karst medium, characteristics of the groundwater flow movement are full with high complexities. Some proper forecasting methods for karst water dynamic have been constantly exploring for many years. This article, taking spring of Jinan for an example, using regression analysis method, analyzes the factors of influencing spring water dynamic, and quantitatively evaluates the influencing coefficients of spring water table concerning rainfall, exploitation and recharge as well as the natural decay coefficient of spring water in dry period. The multiple factors coupling prediction model is built by coupling natural and anthropogenic factors of influencing groundwater table, being used for forecasting spring water dynamic of Jinan. The calculated value of model is highly matching for observation value. In consideration of the characteristics of uneven precipitation in Jinan, suitable ground water recharge zones and volume were investigated finally, which has guiding significance for sustaining spewing of Jinan springs.

Keyword: Coupling model, karst large spring, water level dynamic.

1. INTRODUCTION

Karst water dynamic is the comprehensive reaction of both geological environmental conditions and forming conditions of water resource. The human activities strengthen the complexity and forecasting difficulty of groundwater dynamics. People made large research work about model methods of groundwater table prediction, 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 being improved.

Jinan is famous for springs the spring plays an important role in economic and culture. Under natural conditions, Baotu spring is a perennial spring. With the social development, more and more groundwater is extracted, especially between 1970s and 1990s. Due to the influence of overexploitation of groundwater, from 1972 to 2003, Baotu spring had been drying up. In order to recover the spring water, the conservative measure closing groundwater exploited wells in the groundwater source site was taken in early this century. The spring didn't recovery flowing until in September 2003 [13]. At present, although the groundwater exploitation decreases largely, there still is a threat that spring will stop flowing in dry season, which is a big problem that is not solved fundamentally. The main reasons are that the hydrogeological conditions are complicated and variable regulations of groundwater dynamic 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. This article firstly analyzes the factors influencing groundwater dynamic, based on 40 years' data of groundwater dynamic. The result shows that anthropogenic influence on groundwater level has vast difference in different historical period. Therefore, multiple factors coupling prediction model is estimated in order to explore forecasting methods of karst large spring dynamic.

2. SUMMARY OF RESEARCH ZONE

The city of Jinan is located in northern edge of the central Shandong mountainous region. The terrain of south is higher than north. From south to north, the main exposed formations are the Archean Taishan Group(Art), Cambrian system of palaeozoic era, ordovician, carboniferous and quaternary strata in Jinan Springs area. The south that the limestone exposes is the main rainfall recharge zone of the Spings

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area.The groundwater flowing to north is blocked by the northern rock of Yanshanian, forming the karst large spring (Fig. **1**).The spring water dynamic that shows exploitation-meteorology type is affected obviously by exploitation and climate(rainfall) (Fig. **2**).

3. ANALYSIS OF SINGLE FACTOR INFLUENCING SPRING WATER LEVEL

According to the observation data from 1959 to 2014, factors influencing spring dynamic are specially analyzed. The affected coefficients of different factors on spring water level are obtained by using regression analysis of single

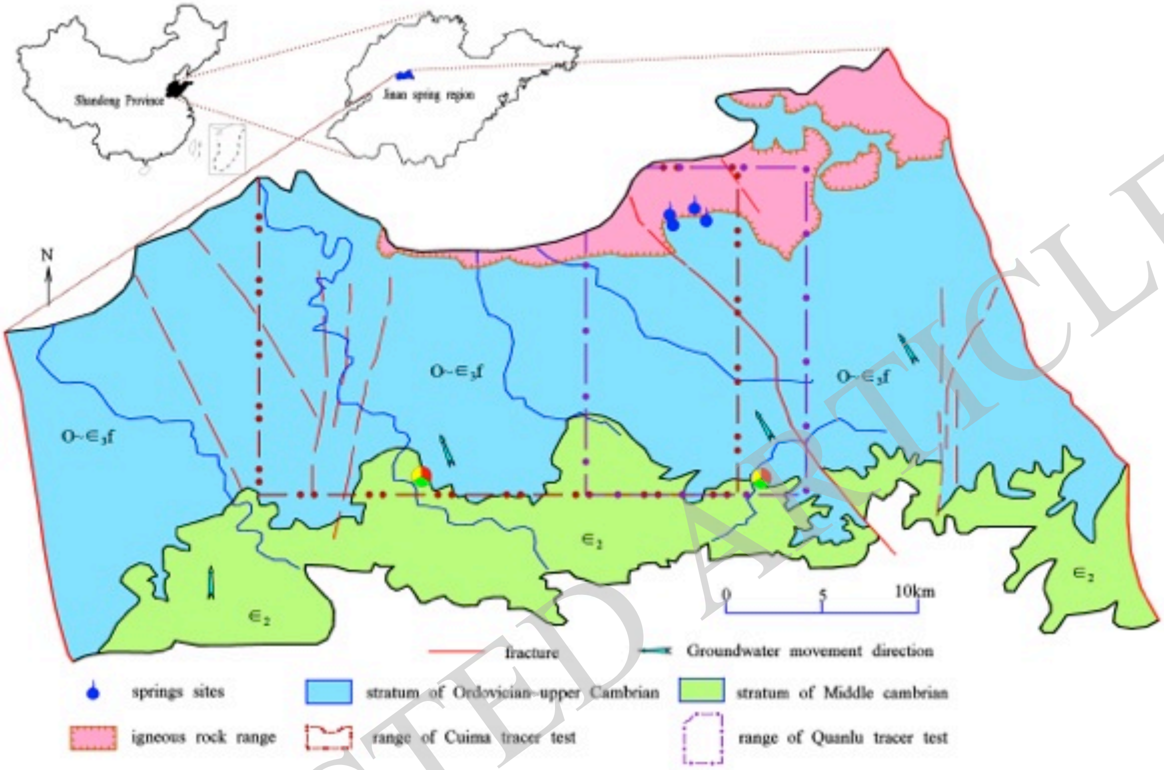

Fig. (1). Geological scheme of Jinan Springs area.

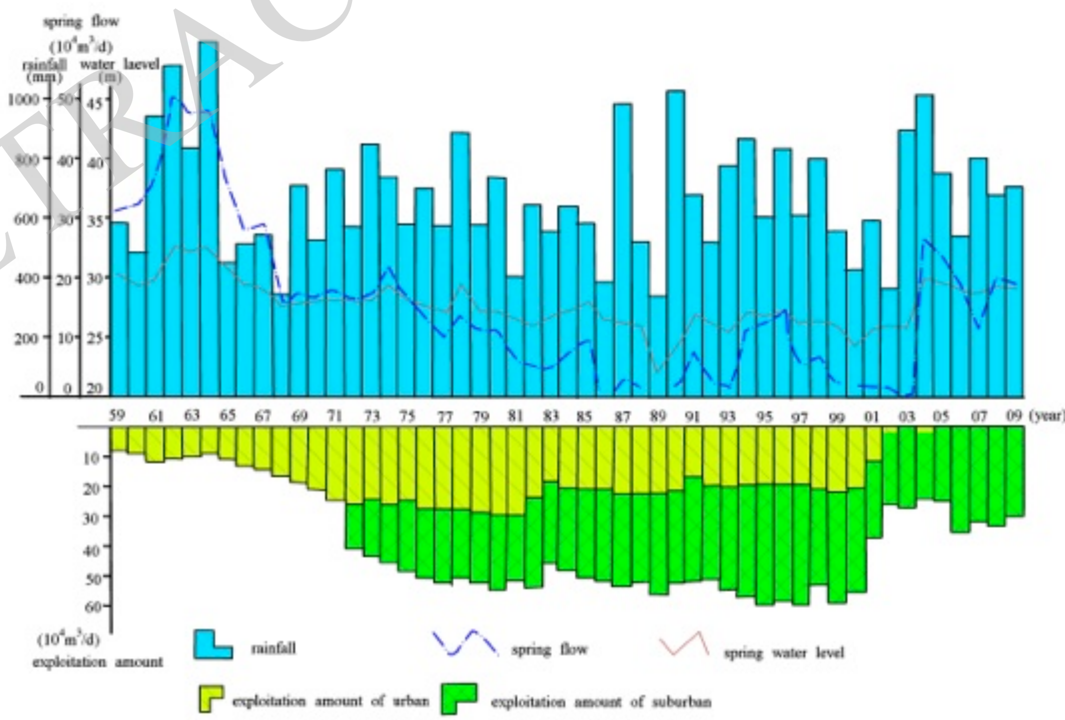

Fig. (2). The spring water table, exploitation and rainfall from 1958 to 2010.

factor. The data come from observation data collected from water and geology department insuring that the data is correct and reliable.

3.1. Influence of Rainfall on Spring Water Level

Rainfall is the main recharge source of groundwater in Jinan spring zone. Therefore, analysis of rainfall features is extremely significant in groundwater level dynamic research of Jinan city. According to observation data precision, the relationship between variable amplitude of spring water level and rainfall was analyzed in different time scales, in order to acquire the correlation between rainfall and spring water level variation.

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

As can be 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, especially large exploitation, also affect variation amplitude of groundwater level in addition to rainfall. The correlation between rainfall and spring water level is not obvious during the period of large exploitation.

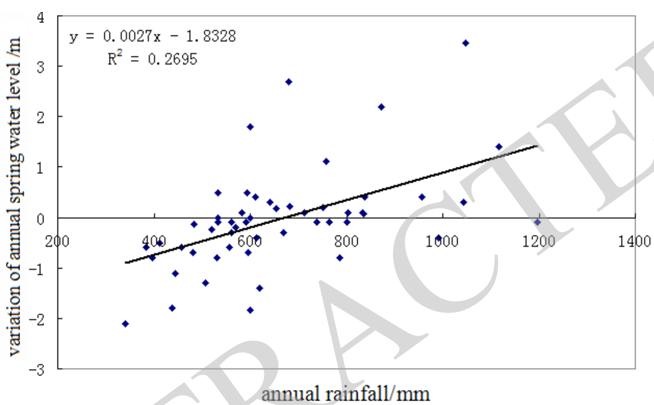

Fig. (3). The correlation between annual rainfall and annual variation of spring water level from 1959 to 2012.

From 1959 to 1967, the average exploitation of urban zone is only 89,500 m³. The affected degree of exploitation is equivalent. Therefore, this period of time is selected to make regression analysis between annual variation of spring water level and annual rainfall (Fig. **4**). The result shows that annual variation of spring water level and annual rainfall are positive correlation, and the correlation coefficient (R^2) is 0.961. The regression equation is showed as follows.

y=0.0033x-2.4357. (1)

In this equation, ***y*** is acted as variation of annual water level, and it's unit is m. And ***x*** is acted as annual rainfall, and it's unit is mm.

In this period of time, annual rainfall and annual variation of spring water level show excellent linear trend, which shows there is a closely linear relationship between annual rainfall and annual variation of spring water level in Jinan city during historical period that human influence is weak. That reflects there lies mathematical and physical relation in between rainfall and karst aquifer, the geological model of Jinan spring area. However, since 1980s, with the increasing anthropogenic influence, the factor that affects karst aquifer of Jinan spring area has been changed. As a result, the mathematical and physical relation of the model is more complicated, needing quantitative analysis in different aspects, such as multiple angles, multiple scales, multiple dimensions and so on. The monthly variation of water level is selected to be studied from 2008 to 2012. Monthly rainfall (***x***) is acted as horizontal coordinate and monthly variation of water level (***y***) is acted as vertical coordinate. Scatter diagram is made (Fig. **5**). It's not tough to find that there is a linear relation in them. The trend line is matched to show their relation. The equation is showed as follows. The multiple correlation coefficient(R^2) is 0.6865.

y=0.0038x-0.1411 (2)

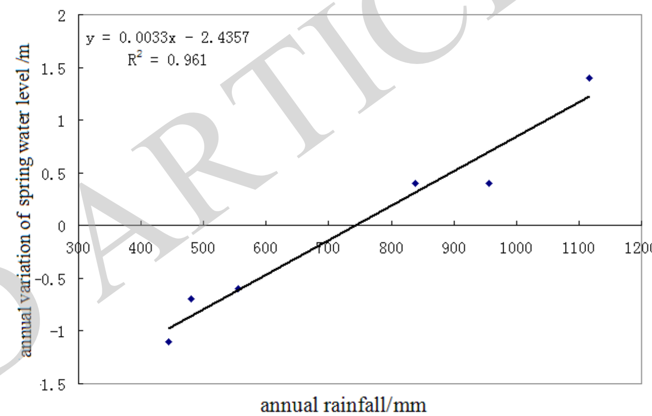

Fig. (4). The correlation between annual rainfall and annual variation of spring water level from 1959 to 1967.

In this equation, ***y*** is severed as monthly variation of water level, and it's unit is m. And ***x*** is severed as monthly rainfall, and it's unit is mm.

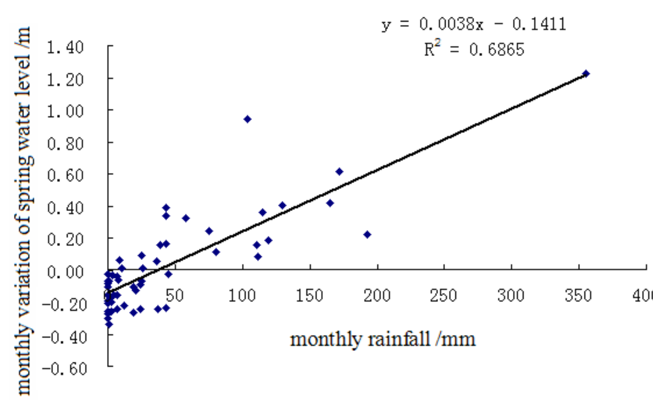

Fig. (5). The correlation between monthly rainfall and monthly variation of spring water level from 2008 to 2012.

It's obvious that the correlation between monthly rainfall and monthly variation of spring water level is well. This implies that a certain amount of rainfall can cause a certain amount lift of groundwater level. And the rainfall needs to be over a certain threshold that is a amount meeting the interception of vegetation and unsaturated zone and so on.

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

$$y=0.0033x-2.4357 \quad (3)$$

Divide both sides of equation by 365.And the gotten equation is showed as follows.

$$\frac{y}{365}=0.0033\frac{x}{365}-\frac{2.4357}{365} \quad (4)$$

In order to unify unit as daily(/d), make a replace: $\Delta h_{daily}=\frac{y}{365}$, $P_{daily}=\frac{x}{365}$

And the gotten equation is showed as follows;

$$\Delta h_{daily}=0.0033P_{daily}-0.00667 \quad (5)$$

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

$$y=0.0038x-0.1411. \quad (6)$$

Divide both sides of equation by 30.And the gotten equation is showed as follows.

$$\frac{y}{30}=0.0038\frac{x}{30}-\frac{0.1411}{30}. \quad (7)$$

In order to unify unit as daily(/d), make a replace: $\Delta h_{daily}=\frac{y}{30}$, $P_{daily}=\frac{x}{30}$

And the gotten equation is showed as follows.

$$\Delta h_{daily}=0.0038P_{daily}-0.0047 . \quad (8)$$

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

$$\begin{cases}\Delta h_{daily}=0.0033P_{daily}-0.00667\\ \Delta h_{daily}=0.0038P_{daily}-0.0047\end{cases} \quad (9)$$

Slope values of the two equations are 0.0033 and 0.0038, with the same order of magnitude, which means the value of water level lifting caused by a unit effective rainfall is 0.0033m~0.0038m, And the order of magnitude of the two constant terms (-0.0047and -0.00667) is also 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 from1959 to 2002. This diagram implies that influencing degree of exploitation on spring water level changed because of the varied layout of groundwater exploitation wells. The wells of exploitation were located in urban zone (nearby outcrop of spring)from 1959 to 1967.And the relation equation of this stage is showed as follows.

$$y=-0.7146x+37.526 \quad (10)$$

The correlation coefficient(R^2) is 0.778.

The exploitation wells of suburb that is far from urban zone increased from 1968 to 2002.The correlation equation is showed as follows.

$$y^{※}=-0.0577x+30.155 \quad (11)$$

And the correlation coefficient (R^2) is 0.5019.

In the equations, ***y*** is acted as spring water level, and the unit is m. ***x*** is acted as exploitation, and the unit is 10,000m^3.

The equation shows there is a negative correlation between exploitation and spring water level The larger exploitation is, the lower spring water level will be. The correlation coefficient (R^2) of urban exploitation to spring water level is up to 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.

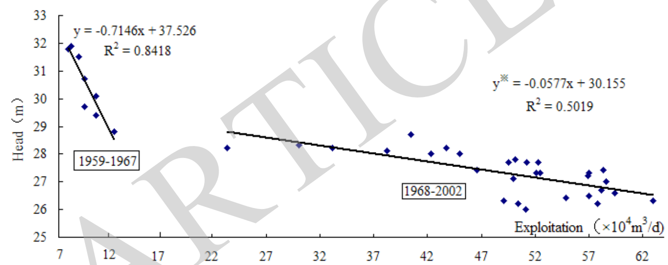

Fig. (6). The relationship between the average annual spring water level and exploitation.

Based on purpose of protecting spring, the relevant department has been increasing the providing amount of surface water(Yellow river water), changing layout of exploitation wells and carrying out artificial recharge since then 2003, therefore, disturbing the groundwater dynamic. Scatter diagram of groundwater exploitation and spring water level from 2003 to 2012 is made (Fig. **7**).

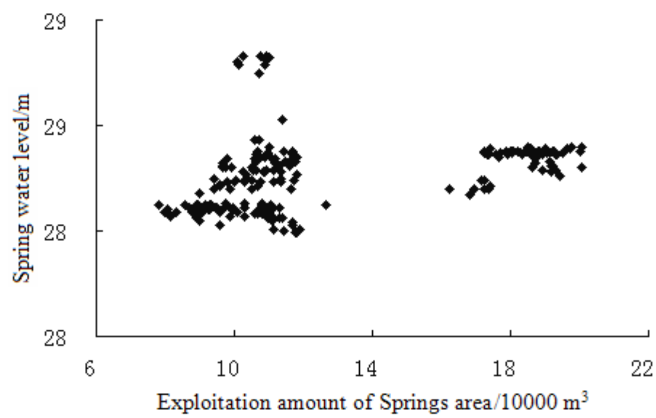

Fig. (7). The relationship between groundwater exploitation and the spring water level from 2003 to 2012.

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

In order to avoid the influence of artificial recharge and exploited layout, the period of time that there only was urban exploitation is selected to analyze influence of average daily exploitation to annual variation of spring water level (Fig. **8**).

The equation is showed as follows.

$$y=-0.5336x+5.1281 \quad (12)$$

And the correlation coefficient (R^2) is 0.8105.

Divide both sides of equation by 365.

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

In order to unify unit as daily(/d), make a replace: $\Delta h_{daily}=\frac{y}{365}, Q_{daily}=x$

The gotten equation is showed as follows:

$$\Delta h_{daily}=0.00146Q_{daily}+0.014 \quad (14)$$

It's found that spring water level decreases 0.00146 m caused by exploitation specified exploitation and the constant term is 0.014.

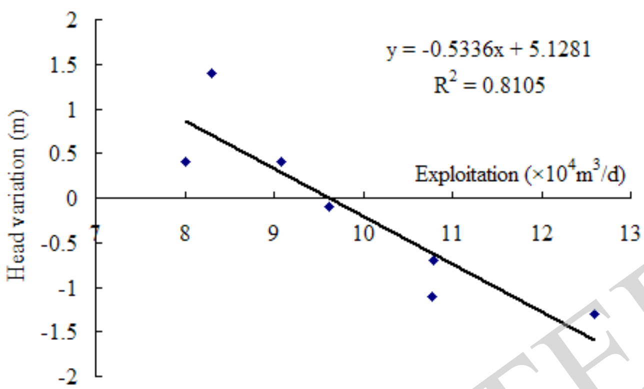

Fig. (8). The relationship between groundwater exploitation and variation of spring water level from 1959 to 1967.

3.3. Influence of recharge on Spring Water Level

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

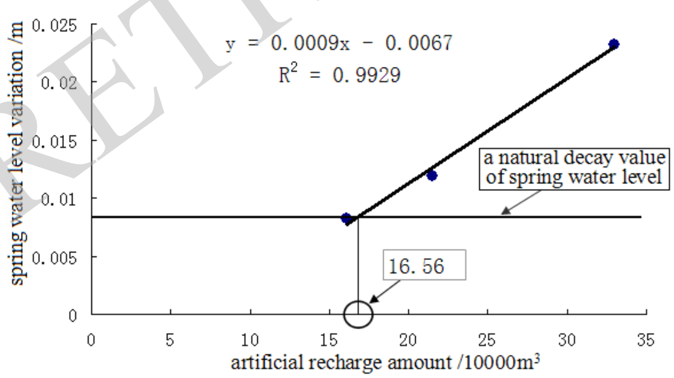

Fig. (9). The relationship between the spring water table variation and the artificial recharge amount.

As can be seen from the Fig. (**9**), artificial recharge amount and spring water table variation shows linear relation. The correlation coefficient(R^2) is 0.993.The equation is showed as follows:

$$y=0.0009x-0.0067 \quad (15)$$

In the equation, y is acted as spring water table variation, and the unit is m. x is severed as artificial recharge amount, and unit is 10,000m^3/d.

In order to unify unit as daily(/d), make a replace: $\Delta h_{daily}=y$, $R_{daily}=x$, the gotten equation is showed as follows.

$$\Delta h_{daily}=0.0009R_{daily}-0.0067 \quad (16)$$

The oblique rate of equation is 0.0009, which means spring water table variation caused by one unit recharge amount is 0.0009m. And the constant value is -0.0067.

4. ESTIMATION AND APPLICATION OF PREDICTION MODEL

4.1. Estimation of Model

Firstly, the initial water level is set as H_0. After Δt days, the water level is that the algebraic sum of the initial water table(H_0) and spring water table variation(Δh) of this period of time. The equation is showed as follows.

$$H=H_0+\Delta h\,. \quad (17)$$

In the equation, H_0 is acted as initial water table, and Δh is acted as spring water table variation after Δt days.

The equations of (8),(14) and (16) are added.

$$\begin{aligned} &rallfall: && \Delta h_{daily}=0.0038P_{daily}-0.0047 \\ &\text{Exploitation:} && \Delta h_{daily}=-0.00146Q_{daily}+0.014 \\ &\text{recharge:} && \Delta h_{daily}=0.0009R_{daily}-0.0067 \end{aligned} \quad (18)$$

The gotten equation is showed as follows.

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

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

After Δt days, spring water table variation caused by rainfall, exploitation as well as artificial recharge is showed as follows.

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

According to analysis of spring water dynamic curve, it's found that with the natural discharge, groundwater level has a natural decay value being acted as λ_D, varying from 0.0078 to 0.0082m/d. After Δt days, natural variation is showed as follows.

$$\Delta h_N=\lambda_D\Delta t \quad (22)$$

The multiple factors coupling prediction model fitting for Baotu spring of Jinan is obtained.

$$H = H_0 + \lambda_D \Delta t + 0.0038\sum_{i=1}^{\Delta t} P_i - 0.00146\sum_{i=1}^{\Delta t} Q_i + 0.0009\sum_{i=1}^{\Delta t} R_i + 0.0026 \quad (23)$$

According to the above analysis and correlation equations of rainfall, exploitation and recharge amount on spring water level variation, various influencing coefficients are gained as follows: influencing coefficient of effective rainfall, being acted as λ_P that it's value is 0.0038 m/mm; the decrease value of spring water table caused by exploitation is affected by layout of exploitation wells and influencing coefficient of exploitation is different because of different locations of exploited wells, andλ_Q (λ_Q= (λ_{Q1}, λ_{Q2}, λ_{Q3},…)) is acted as influencing coefficient. Affected coefficient of artificial recharge amount on spring water level is influenced by locations of recharge. Affected coefficient of artificial recharge amount on spring water level is different in different locations of recharge, being acted as λ_R(λ_R= (λ_{R1}, λ_{R2}, λ_{R3},…)).The groundwater level has a natural decay value, being acted as $\lambda_{D.}$

According to above analysis, a equation is gained as follows.

$$H=H_0-\lambda_D T-\lambda_Q Q+\lambda_R R+\lambda_P P+C \quad (24)$$

In the equation,

$$T(T=\sum_{1}^{t} 1)$$

is served as natural decay function, and the unit is d.

$$R(R=\sum_{j=1}^{t} R_j)$$

is acted as recharge function, and it's unit is 10,000m^3.

$$Q(Q=\sum_{j=1}^{t} Q_j)$$

is exploitation function, and unit is 10,000m^3.

$$P(P=\sum_{j=1}^{t} P_j)$$

is rainfall function, and unit is mm. C is constant value.

Therefore, forecasting equation of different period of time is attained as follows.

$$H_t = H_0 - \lambda_D \sum_{1}^{t} 1 + \lambda_P \sum_{j=1}^{t} P_j - \sum_{i=1}^{i=n} \lambda_{Qi} \sum_{j=1}^{t} Q_j + \sum_{w=1}^{m} \lambda_{Rw} \sum_{j=1}^{t} R_j + C \quad (25)$$

(t,j,i,m,n≥1, being positive integer; Q_j,R_w,P_j≥0)

4.2. Reliability Analysis of Model

Using regression model, combining measured data of exploitation, rainfall and recharge amount, water table of Baotu spring is forecast and made a reliable analysis with measured water level value. Fig. (**10**) shows the forecasting result.

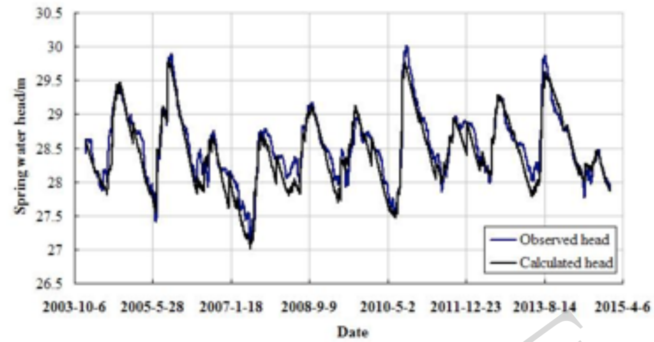

Fig. (10). Time-series graph of calculated and observed Baotu Spring water level from 2004 to 2014.

It implies that time-series graph of calculated and curve of observed Baotu Spring water level are extremely closed. Combining Fig. (**11**), in the 4018 samples, the correlation coefficient(R^2) is 0.9071, and mean absolute error is 0.1516 as well as the standard prediction error is 0.0066.That implies forecasting precision is high being able to be used for prediction of spring water level in the future.

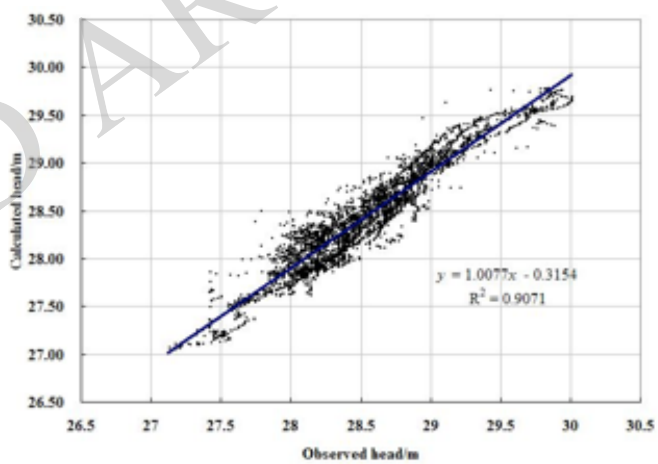

Fig. (11). Calculated *versus* observed Baotu Spring water level.

This model acting rainfall, exploitation and recharge amount as main variables predicts spring water level. The forecasting precision is day. If adopting different combination of rainfall, exploitation and recharge amount, spring water level under different situations is able to be forecast.Table **1**.

4.3. Predication of Spring Water Level Dynamic

Water level observation of about 30 years shows that time of stopping flowing of Jinan spring water all is in dry period that is from April to June. For protecting famous spring, forecasting goal is Baotu spring water table in dry period from January to June,2015. And initial water table (H_0) is elevation value of groundwater level on January 1,2015. Exploitation and recharge amount adopt designed value. Rainfall amount of forecasting period is distributed by monthly rainfall ratio (Table **2**). Fig. (**12**) shows designed value of rainfall probability of 25%, 50%, 90%.

Table 1. Chart of statistical analysis.

Sample Size (N)	Mean Error (ME)	Mean Absolute Error (MAE)	Mean Absolute Relative Error (MARE)	Standard Deviation of Forecast Errors	Correlation Coefficient R^2
4018	-0.0943	0.1516	0.0053	0.0066	0.9071

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

Month	1	2	3	4	5	6	7	8	9	10	11	12
Rainfall ratio (%)	0.26	1.58	1.3	4.31	10.28	9.96	29.44	28.13	10.48	2.3	1.32	0.64

According to model calculation, predicting result (Fig. **13**) of Baotu spring water level shows that under rainfall probability of 90%, Baotu spring water level will be low to the elevation value of Baotu spring vent on about May 30,2015, Baotu spring will stop flowing. Therefore, the emergency recharge measures of protecting spring should been taken to ensure karst large spring won't stopping flowing.

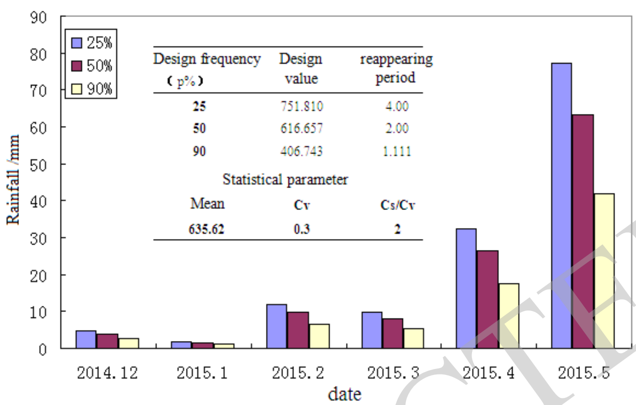

Fig. (12). The designed value of rainfall amount from January to June, 2015.

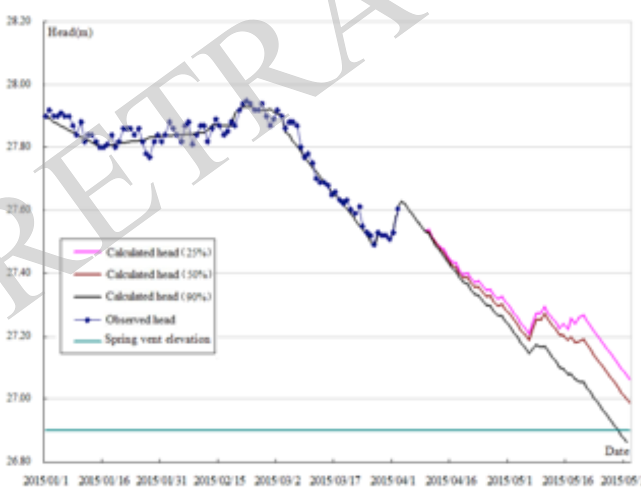

Fig. (13). Time-series graph of calculated and observed Baotu Spring water level.

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 during June 2014 to December. The tracer detection range is as 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:

(1) Fracture-karst development is heterogeneity, including tubular, karst cave, cracks and so on. The degree of karst development differs from different lithology, and that of the same lithology is different because of different tectonic position. Therefore, the apparent groundwater velocity is different.

(2) Along the tectonic fracture zone and influence zone of fracture fissure, good migration pathway of groundwater is formed, in which the apparent groundwater velocity is fast. Structural belt is the ideal source location.

(3) Because of tectonic fracture zone is with good hydraulic conductivity, there is a good hydraulic connection between Zhangxia group limestone aquifer of Cambrian and Ordovician limestone aquifer. Therefore, recharging groundwater in Zhangxia limestone of Cambrian has an effect on spring protection. At the same time, it also shows the correctness of the numerical model research range.

4.5. Determination of Recharge Amount

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

Intersection point of linear equation and x axis is 37.13mm that is rainfall threshold value under the monthly scale (see Fig. **5**). If monthly rainfall in dry season is less than 37.13mm, recharge will be a must to keep spring water steady. 37.13mm rainfall is converted into recharge amount of groundwater is 290,000m^3/d. That is to say it's necessary to carry out groundwater recharge in order to keep spring water table steady, and the recharge amount is 290,000m^3/d. 37.13mm rainfall which is a threshold value under monthly scale is different from threshold value of water level ascension caused by single rainfall. Predecessors studied threshold value of rainfall of water level ascension caused secondary rainfall under different rainfall strength in limestone region. This value is also not equivalent for different developing extent of karst and different thickness of

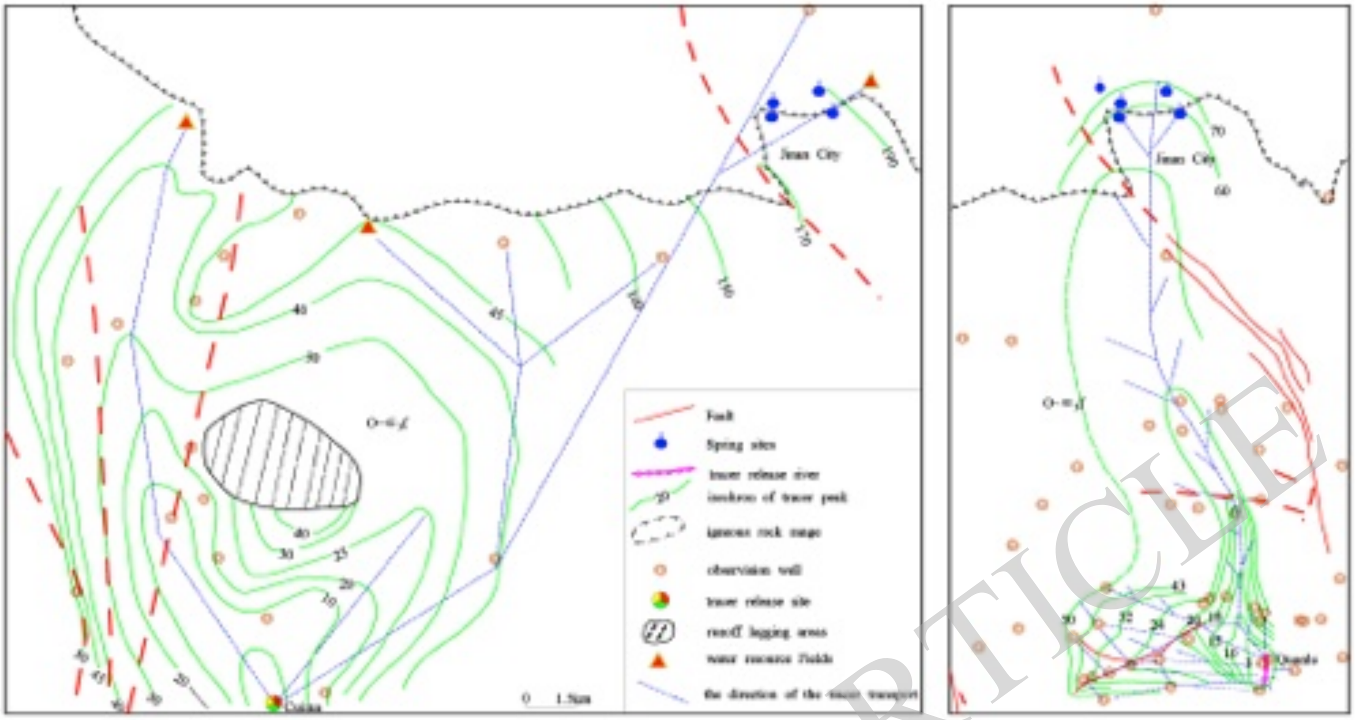

Fig. (14). Time contour of tracer spread to the peak and tracer migration path.

unsaturated zone because the test is in the small area. And this value has a certain limitation concerning practical application of large region engineering.

5. SUMMARY

(1) Based on principle of superposition, predicting model is put forward concerning groundwater dynamic of karst large spring in northern China. According to application of Baotu spring water level of Jinan city, calculated value is highly fitting for observation data. Estimated predicting model has high precision and practical applied value.

(2) This predicting model considers more than factors such as rainfall, artificial exploitation, artificial recharge and so on, above all, aiming at specialty of karst large spring. Flux decay factor of spring is introduced into forecasting model to achieve the coupling between natural factors and anthropogenic influence. And predicting model has certain theoretical significance.

(3) In consideration of uneven rainfall in time and space, during dry ground water levels fall and thus spring discharge attenuation is nature. To avoid spring cutoff in dry season, the implementation of artificial recharge is necessary. In order to select recharge area, specific hydrogeological conditions should be considered. Recharge volume is designed for 290 000 m^3/d.

CONFLICT OF INTEREST

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

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