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Comparative study on models of groundwater salinity in Yongnian County

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Abstract: The stability of groundwater salinity has important practical significance for the healthy development of groundwater in China, especially in areas where groundwater is over-exploited. In order to improve the fitting precision and prediction effect of groundwater salinity, this paper constructed a series of fitting and prediction models of groundwater salinity based on grey theory and MATLAB.Taking Yongnian County of Handan City as an example, this paper adopted the data of groundwater salinity of three monitoring wells in this region from 2010 to 2015 for an empirical study.The fitting results of GM(1,N) model were compared with the fitting results of GM(1,1) and MATLAB linear regression models. The results showed that the absolute relative error of the GM(1,N) model in the three monitoring wells was 0.4391%, 0.2540%, 0.4675%, and the accuracy was A. Compared with other models, the prediction effect is better, which can meet the needs of groundwater mineralization prediction in Yongnian County. The prediction results can provide a scientific basis for the work of groundwater management and groundwater mineralization in Yongnian County in the next few years.

1. Introduction

Due to the lack of surface water resources in Handan City, Hebei Province, groundwater has become a major source of drinking and irrigation water. People have severely over-exploited groundwater, resulting in a continuous decline in groundwater levels . Yongnian County, located in the northern part of Handan City, is a county with very scarce water resources. In recent years, with the continuous urbanization of Yongnian County from east to west and from north to south, the contradiction between population growth and water supply demand is becoming more and more serious [1].Due to the serious shortage of groundwater supply, people over-exploit groundwater and form a water level drop funnel. However, the water in the funnel stays in the ground for a long time, and the dissolved mineral content is high, which leads to an increase in the mineralization degree of the groundwater and seriously threatens the water environment safety in the region [2]. Therefore, it is important to analyze the changing trend of groundwater salinity in this area.

In recent years, grey models [3], statistical methods ,fuzzy theory and artificial neural network models [4] have been introduced into the simulation and prediction of groundwater salinity.The grey theory was proposed by Professor Julong Deng in 1982 [5], it requires less data, but the prediction is accurate highly . The sample distribution does not need to be regular, so it is easy to calculate and test [6]. It has been widely used in research on comprehensive grain production capacity [7], sewage discharge forecast

[8], national cotton production forecast [9], and evaluation of reservoir resettlement support effect [10].

Based on the measured data of groundwater salinity in Yongnian County, Handan City, this paper will formulate three different models of GM(1,N), GM(1,1) and MATLAB linear regression to fit the groundwater mineralization degree, and select the highest precision model as the prediction model of groundwater salinity. This study aims to understand the evolution law of groundwater mineralization in Yongnian County, it provides reference basis for the rational utilization of groundwater resources, the management of over-exploited groundwater problems and the prediction of groundwater mineralization.

2. Regional overview and data collection

2.1 Research area overview

Yongnian County is located in the eastern plain of Handan City, which in the mid-latitude zone, and is a warm temperate semi-humid semi-dry continental monsoon climate zone. The total climate characteristics of the year are: dry climate, low rainfall, typical of dry areas. There are fewer depressions in the plains, the larger depressions are mainly Yongnian [11], and the groundwater mineralization is higher. The Ming River, seasonal water, is its main water system, flowing through Yongnian and Jize, and then flows into Xingtai City [12]. In recent years, due to the increasing urban population, the groundwater is over-exploited, so that the hydrogeological changes of the Ming River alluvial-producing fan are severe, and the change of groundwater salinity seriously affects the growth of crops and people's normal life. The specific geographical location is shown in Figure 1 below.

2.2 Basic data collection

This paper collected the Water Resource Bulletin of Handan City (2010-2015) and statistical yearbook data, selected three groundwater monitoring wells in Yongnian County and obtains the measured data of each well, which are Lin Mingguan monitoring well, Liu Cun monitoring well and Lian Huakou monitoring well, respectively.The specific location of the monitoring wells is shown in Figure 1.

Figure 1. Location map of Yongnian County administrative division and monitoring wells

There are many factors affecting the salinity of groundwater, such as soil salinity,pH,groundwater level,chloride,groundwater extraction, regional rainfall[13].In recent years,there is a serious water shortage in this area, leading to excessive use of groundwater for industrial and agricultural,which has a great impact on the mineral degree of groundwater. Therefore, the main factors considered in this paper are water level, regional rainfall and well production of monitoring well, ignoring other factors. The monitoring frequency of the salinity and water level data of the three wells was once every 5 days.In order to better reflect the overall changes in different years, the salinity and water level are taken as the average of each year, besides,the rainfall and mining amount are the total annual rainfall and mining amount of Yongnian County.So,the statistics of groundwater salinity and related factors in 2010-2015 are shown in table 1.

Table1. 2010-2015 table of groundwater mineralization and related factors

name	monitoring indicators	2010	2011	2012	2013	2014	2015
Lin Mingguan	salinity ($mg \cdot L^{-1}$)	732.5	840.6	1028.8	897.7	1554.9	1905.6
	rainfall (mm)	410.8	538.8	500.2	553.7	368.8	395.5
	mining volume($10^8 m^3$)	1.8460	1.7437	1.5827	1.5363	1.6984	1.3905
	water level (m)	25.887	27.633	28.564	25.958	25.396	29.788
Liu Cun	salinity ($mg \cdot L^{-1}$)	474.5	552.8	398.3	468.9	481.7	580.9
	rainfall (mm)	410.8	538.8	500.2	553.7	368.8	395.5
	mining volume($10^8 m^3$)	1.8460	1.7437	1.5827	1.5363	1.6984	1.3905
	water level (m)	34.271	35.328	35.568	35.771	40.788	50.932
Lian Huakou	salinity ($mg \cdot L^{-1}$)	1160.7	1208.6	1196.4	1245.1	1280.7	1345.0
	rainfall (mm)	410.8	538.8	500.2	553.7	368.8	395.5
	mining volume($10^8 m^3$)	1.8460	1.7437	1.5827	1.5363	1.6984	1.3905
	water level (m)	6.021	7.792	8.923	8.982	9.178	9.584

From the basic data, we can see that the salinity difference between Liu Cun and Lian Huakou is large. The main reason is that Yongnian County has a complex geographical location, and the urbanization has been advancing towards the west in recent years, which results in a certain impact of surrounding environment and population on the degree of mineralization. According to the principle of principal component analysis [14], these factors are temporarily excluded.

3. Model theory and establishment

3.1 The establishment of GM(1,1) gray model

GM (1,1) model as the most basic of the grey forecasting model which the principle is to create a set of new data sequences with obvious trends in a cumulative way by the initial data sequence of the objective system, and it can be predicted that according to the growth trends for the new data sequence to build a model, and then take up with the decrements arithmetic to create the reverse calculation , and recover the raw data sequence to obtaining the prediction result [15~16].

GM (1,1) modeling process:

(1) Let $x_0=(x_0^{(1)}, x_0^{(2)} \dots x_0^{(n)})$ be a set of raw data, and n is the data.

(2) Let $x_1=(x_1^{(1)}, x_1^{(2)} \dots x_1^{(n)})$ be a 1-AGO sequence of x_0; the Equal-Average Equal-Weighted sequence of x_1 is listed as: $z_1=(z_1^{(2)}, z_1^{(3)} \dots z_1^{(k)})$; and $z_1^{(k)}=0.5x_1^{(k-1)}+0.5x_1^{(k)}$ (k=2, 3…n).

(3) It is created a first-order unary differential equation GM(1,1) to x_1 for the whitening form of t which according to the grey theory:

$$\frac{dx_1^{(1)}}{dt} + ax_1^{(1)} = b \qquad (1)$$

(a, b is the unresolved coefficient which called the development coefficient and the grey actuating quantity respectively). To solve the grey parameter $\hat{a}$ by the least squares method, then

$$\hat{a} = [a,b]^T = (B^T B)^{-1} B^T Y \qquad (2)$$

$$Y = \begin{bmatrix} X_0^{(2)} \\ X_0^{(3)} \\ \dots \\ X_0^{(n)} \end{bmatrix} \qquad (3) \qquad B = \begin{bmatrix} -\frac{1}{2}(X_1^{(1)}(1)+X_1^{(1)}(2)) & 1 \\ -\frac{1}{2}(X_1^{(1)}(2)+X_1^{(1)}(3)) & 1 \\ \dots & \\ -\frac{1}{2}(X_1^{(1)}(n-1)+X_1^{(1)}(n)) & 1 \end{bmatrix} \qquad (4)$$

The prediction formula is created that get the time response series of GM(1,1)model as follows, where $x_0^{(1)}$ is unchanged, and k=1，2…n

$$\hat{x}_1^{(k+1)} = [x_0^{(1)} - b/a]\exp - ak + b/a \qquad (5) \qquad\qquad \hat{x}_0^{(k+1)} = \hat{x}_1^{(k+1)} - \hat{x}_1^{(k)} \qquad (6)$$

3.2 Establishment of GM(1,N) Grey Model

The GM(1,N) model is an enhanced version of GM(1,1) which describes the effects from N related variables and time series t on the research variables. The essence of the GM(1,N) model is: Let the research variable be $x_1^{(0)}$, and $x_1^{(0)}=(x_1^{(0)}(1), x_1^{(0)}(2)\ldots x_1^{(0)}(n))$, and its related factor sequence can be represented as $x_2^{(0)}$, $x_3^{(0)}\ldots x_N^{(0)}$。$x_1^{(0)}$, and generate a sequence $x_1^{(1)}$[17~18] after accumulated generating operation. The accumulated generation variables of which research variables and related factors can create differential equations as following:

$$\frac{dx_1^{(1)}}{dt} + ax_1^{(1)} = b_1x_2^{(1)} + b_2x_3^{(1)} + \ldots b_{N-1}x_N^{(1)} \qquad (7)$$

The parameter in equation (7) can be represented as $a = [a, b_1, b_2 \ldots b_{N-1}]^T$, and

$$B = \begin{bmatrix} -\frac{1}{2}(X_1^{(1)}(1) + X_1^{(1)}(2)) & X_2^{(1)}(2) & \ldots & X_N^{(1)}(2) \\ -\frac{1}{2}(X_1^{(1)}(2) + X_1^{(1)}(3)) & X_3^{(1)}(3) & \ldots & X_N^{(1)}(3) \\ \ldots & \ldots & \ldots & \ldots \\ -\frac{1}{2}(X_1^{(1)}(n-1) + X_1^{(1)}(n)) & Xn^{(1)}(n) & \ldots & X_N^{(1)}(n) \end{bmatrix} \qquad (8)$$

$$Y = [X_1^{(0)}(2), X_1^{(0)}(3) \ldots X_1^{(0)}(n)]^T \qquad (9)$$

Then the parameters $a = [a, b_1, b_2 \ldots b_{N-1}]^T$ is estimated by least squares that get $\hat{a} = (B^T B)^{-1} B^T Y$. The approximately time response of the GM(1,N) model shows in Formula(10), and the cumulative regression forecasting value shows in Formula(11);

$$\hat{x}_1^{(1)}(k+1) = \frac{1}{a}\sum_{i=2}^{N} b_{i-1}x^{(1)}{}_i(k+1) + [x_1^{(1)}(1) - \frac{1}{a}\sum_{i=2}^{N} b_{i-1}x^{(1)}{}_i(k+1)\exp - at] \qquad (10)$$

$$\hat{x}_1^{(0)}(k+1) = a^{(1)}\hat{x}_1^{(1)}(k+1) = \hat{x}_1^{(1)}(k+1) - \hat{x}_1^{(1)}(k) \qquad (11)$$

3.3 Establishment of MATLAB linear regression model

Linear regression is a statistical analysis method that USES regression analysis in mathematical statistics to determine the quantitative relationship between two or more variables that depend on each other. It is widely used [19]. For example, when forecasting the flood peak of a reservoir, rainfall, land use, DEM data and so on will all have an impact on the flood peak flow and current peak length. This paper conducts linear regression analysis based on MATLAB .Let the dependent variable be y, the independent variable with the number of m is x, Their observed value in n sets are（$x_{1i}, x_{2i} \ldots x_{mi}, y_i$）($i$=1,2…$n$) ,which the expression of multiple linear regression is in (12), and the form of matrix can be represented as: $y = x\beta$ as shown in the following equation (13), where β is the regression coefficient of the multiple linear regression equation .

$$\begin{cases} y_1 = \beta_0 + \beta_1x_{11} + \beta_2x_{12} + \ldots + \beta_m x_{1m} \\ y_2 = \beta_0 + \beta_1x_{21} + \beta_2x_{22} + \ldots + \beta_m x_{2m} \\ \ldots \\ y_n = \beta_0 + \beta_1x_{n1} + \beta_2x_{n2} + \ldots + \beta_m x_{nm} \end{cases} \qquad (12)$$

$$\beta=\begin{bmatrix}\beta_0\\ \beta_1\\ \cdots\\ \beta_m\end{bmatrix} \qquad y=\begin{bmatrix}y_1\\ y_2\\ \cdots\\ y_n\end{bmatrix} \qquad x=\begin{bmatrix}1 & x_{11} & x_{12} & & x_{1m}\\ 1 & x_{21} & x_{22} & & x_{2m}\\ 1 & x_{31} & x_{32} & \cdots & x_{3m}\\ \cdots & \cdots & \cdots & & \cdots\\ 1 & x_{n1} & x_{n2} & & x_{nm}\end{bmatrix} \qquad (13)$$

4. Comparative study of model examples

4.1 Model running results

By inputting the data of table 1 into the established GM(1,1), GM(1,N) and MATLAB linear regression models, we can run the model fitting of the salinity in the groundwater of three monitoring wells in Yongnian District. The fitting interval is from 2010 to 2015. The fitting results and relative errors are shown in Table 2~ 4 below, and the fitting curve is shown in Figure 2~4 below.

4.2 Comparison of fitting accuracy

It can be seen from table 2~4 and figure 2~ 4，The absolute values of mean relative errors of Lin Mingguan monitoring well, Liu Cun monitoring well and Lian Huakou monitoring well under the GM (1,N) model are 0.4391%, 0.2540% and 0.4675%, respectively. The absolute value of mean relative error under GM (1,1) model are 10.3164%, 9.5865% and 0.9153%. And under the MATLAB linear regression model are 12.5750%, 2.4919%, and 1.8112%. Therefore, GM(1, N) model has the highest fitting accuracy. The main reason is that the GM (1, 1) model only considers the time changes the single factor's influence on the groundwater salinity, though MATLAB linear regression model for the multiple factors, it is more suitable for linear relationship better series, and GM (1, N) model not only considers many factors work together and to nonlinear series high forecast precision. Therefore, it shows that GM(1, N) model has the highest fitting accuracy for groundwater salinity in Yongnian County, and can be better applied to the study of spatio-temporal dynamic changes of groundwater salinity in this area.

Standard deviation and residual test: To verify the compliance of GM (1, N) models, perform the standard deviation and residual test for the model [20].

By calculation, it is known that the standard deviation of original data in the
wells of Lin Mingguan, Liu Cun and Lian Huakou are respectively S_{11}=465.3284, S_{12}=65.3011 and S_{13}=66.1527; The standard deviations of residual e_0 are S_{21}=0.0066, S_{22}=0.0045and S_{23}=0.0074 respectively. The variance ratio $C_1=1.4206*10^{-5}$, $C_2=6.8758*10^{-5}$,$C_3=1.1174*10^{-4}$,all less than 0.35.It shows that GM(1, N) model can pass the standarddeviation and residual test, and the model has a high precision.

On the basis of the above verification that GM(1, N) model had the highest fitting accuracy for groundwater salinity of three monitoring Wells in Yongnian County, we used GM(1, N) model to predict groundwater salinity of the region in the five years of 2016-2020, and obtained the predicted values of the three monitoring wells as shown in table 5 below. Based on the measured values of groundwater salinity of each monitoring well from 2010 to 2015, the variation of groundwater salinity from 2010 to 2020 can be roughly obtained as shown in figure 5 below.

Table2. Comparison of the fitting results and measured values of each model in Lin Mingguan monitoring well

Year	Measured value ($mg \cdot L^{-1}$)	GM(1,N) model fitted value ($mg \cdot L^{-1}$)	GM(1,N) model Absolute value of relative error（%）	GM(1,1) model fitted value ($mg \cdot L^{-1}$)	GM(1,1) model Absolute value of relative error（%）	MATLAB linear regression fitted value ($mg \cdot L^{-1}$)	MATLAB linear regression Absolute value of relative error（%）
2010	732.5	732.5	0	732.5	0	919.96	25.5918
2011	840.6	848.8	0.9755	734.2	12.6576	621.18	26.1028
2012	1028.8	1021.4	0.7193	923.5	10.2352	1091.51	6.0955
2013	897.7	901.7	0.4456	1161.5	29.3862	937.53	4.4369
2014	1554.9	1549.5	0.3473	1460.9	6.0454	1363.09	12.3358
2015	1905.6	1908.4	0.1469	1837.5	3.5737	1888.70	0.8869
Absolute value of average relative error（%）		0.4391		10.3164		12.5750	

Table3. Comparison of the fitting results and measured values of each model in Liu Cun monitoring well

Year	Measured value ($mg \cdot L^{-1}$)	GM(1,N) model fitted value ($mg \cdot L^{-1}$)	GM(1,N) model Absolute value of relative error（%）	GM(1,1) model fitted value ($mg \cdot L^{-1}$)	GM(1,1) model Absolute value of relative error（%）	MATLAB linear regression fitted value ($mg \cdot L^{-1}$)	MATLAB linear regression Absolute value of relative error（%）
2010	474.5	474.50	0	474.50	0	462.6392	2.4996
2011	552.8	551.79	0.1827	466.28	15.6512	562.9497	1.8361
2012	398.3	401.43	0.7858	480.87	20.7306	419.4711	5.3154
2013	468.9	468.58	0.0682	495.92	5.7624	452.7142	3.4519
2014	481.7	479.81	0.3924	511.43	6.1719	488.8092	1.4759
2015	580.9	581.45	0.0947	527.44	9.203	578.7367	0.3724
Absolute value of average relative error（%）		0.2540		9.5865		2.4919	

Table4. Comparison of the fitting results and measured values of each model in Lian Huakou monitoring well

Year	Measured value ($mg \cdot L^{-1}$)	GM(1,N) model fitted value ($mg \cdot L^{-1}$)	GM(1,N) model Absolute value of relative error（%）	GM(1,1) model fitted value ($mg \cdot L^{-1}$)	GM(1,1) model Absolute value of relative error（%）	MATLAB linear regression fitted value ($mg \cdot L^{-1}$)	MATLAB linear regression Absolute value of relative error（%）
2010	1160.7	1160.7	0	1160.7	0	1185.8	2.1625
2011	1208.6	1198.5	0.8357	1183.9	2.0437	1203.4	0.4302
2012	1196.4	1209.7	1.1117	1218.5	1.8472	1267.6	5.9512
2013	1245.1	1240.6	0.3614	1254.0	0.7148	1261.0	1.277
2014	1280.7	1284.1	0.2655	1290.6	0.773	1292.1	0.8901
2015	1345.0	1341.9	0.2305	1328.3	1.2416	1347.1	0.1561
Absolute value of average relative error（%）		0.4675		0.9153		1.8112	

Table5. Predictive values in GM(1,N) model for 2016-2020

Year	2016	2017	2018	2019	2020
Lin Mingguan ($mg \cdot L^{-1}$)	2152.3	2360.9	2532.2	2667.7	2771.7
Liu Cun ($mg \cdot L^{-1}$)	471.42	474.97	434.2	407.48	376.05
Lian Huakou ($mg \cdot L^{-1}$)	1063	1116.6	947.6	926.1	816.6

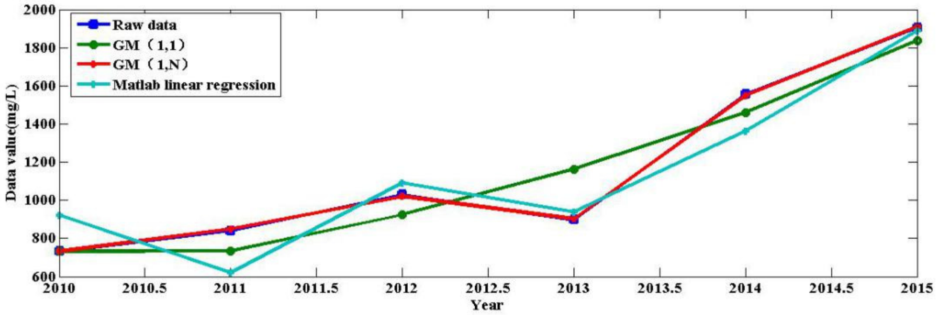

Figure 2. Lin Mingguan monitoring well fitting curve

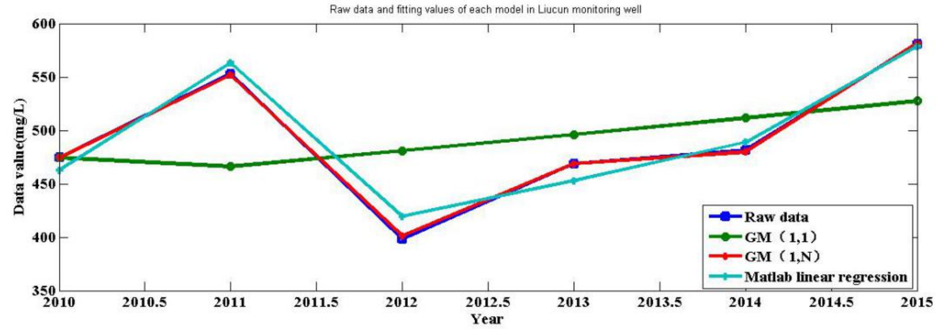

Figure 3. Liu Cun monitoring well fitting curve

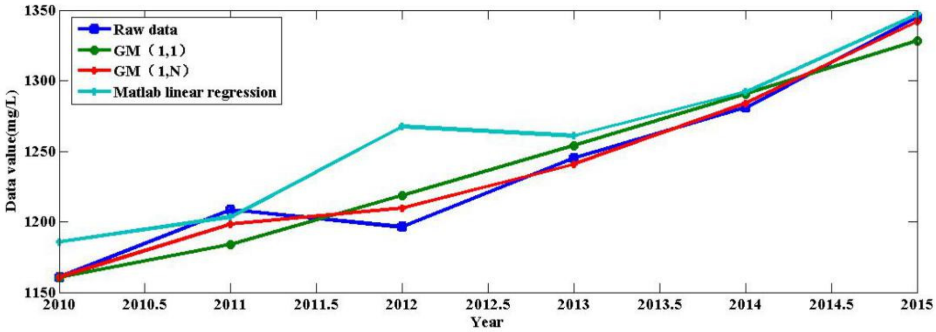

Figure 4. Lian Huakou monitoring well fitting curve

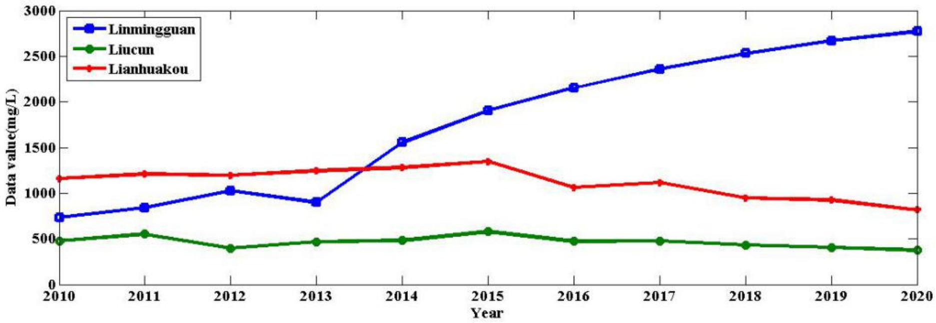

Figure 5. The general trend of mineralization in three monitoring wells from 2010 to 2020

It can be seen from figure 5 that the mineralization base of groundwater in the monitoring wells of Lin Mingguan is not large, but it shows a trend of continuous rise. It is necessary to pay attention to the situation of groundwater exploitation in this area and take measures to control it; As Lian Huakou is located at the downstream of Handan city, it receives the sewage discharged by the city and the water is seriously polluted, and the groundwater mineralization base of this area is large. Single from the salinity of the water quality evaluation factors, water belongs to Ⅴ class, potable. However, from the perspective of prediction, the groundwater salinity of Lia Hua Kou is decreasing. It indicates that the problem of groundwater exploitation in this area is being concerned and implemented. The groundwater salinity base of Liu Cun is low, the water quality is good, there is no significant change, it can be used for centralized drinking water source and industrial and agricultural water.

The changes in the above three regions indicate that the groundwater in Yongnian County is not evenly distributed, the mining conditions are very different, and the changes of mineralization are unstable. This is not only different from the geographical location of the three regions, but also related to the external environment. Therefore, it is still necessary to improve the treatment of over-exploited groundwater and avoid the stress of the external environment on the degree of mineralization of groundwater.

5. Conclusions and suggestions

The paper established the groundwater mineralization fitting and prediction model with the grey system and MATLAB linear regression. The main conclusions are as follows:

(1) In this paper, GM(1,1), GM(1,N) and MATLAB linear regression models were established with gray system and MATLAB, as the fitting and prediction model of groundwater mineralization in Yongnian County. Based on the advantages and disadvantages of each model, GM(1,N) model was determined to be the accurate prediction model in this region.

(2) The fitting error of GM(1,N) model was minimal. The absolute value of the fitting average relative error in the three monitoring wells in Yongnian County was 0.4391%, 0.2540% and 0.4675%, respectively, and the average was 0.3869%, close to 0. The fitting accuracy was significantly higher than GM(1,1) and MATLAB linear regression models.

(3) Using the GM (1, N) model to predict the groundwater salinity of the Yongnian area, it will be able to master the changes in the future of groundwater in the future. It can be seen from the prediction results of the model that the groundwater salinity of the monitoring wells in Lin Mingguan was continuously increasing. It is expected that the groundwater salinity will be 2771.70 mg/L by 2020, which is a big change; There was a small decrease in Liu Cun and Lian Huakou. It is estimated that the groundwater salinity will be 376.05 mg/L and 816.60 mg/L by 2020, respectively. This indicates that the groundwater salinity is unstable. Therefore, it is still necessary to strengthen the treatment of serious over-exploitation of groundwater due to the promotion of urbanization so as to avoid the stress of external environment on the mineralization of groundwater. This research is aimed at providing guidance for the reasonable arrangement of groundwater, groundwater quality control and healthy and stable regulation of water resource market in Yongnian County in the coming years.

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