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Application of Coupled Model of Deterministic and Stochastic Model in Predicting Groundwater Regime in Hengshui City

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Abstract: Groundwater is the important water supply source of many cities in north China and it plays an important role to the development of economy and society. The groundwater level fluctuation reflects groundwater resources variation. The research of groundwater level prediction is complicated mainly because the complication, nonlinear, multi-scale, mutability and stochastic phenomena are evidence in groundwater system. It is significantly valuable to improve the accuracy and reliability of groundwater level prediction and develop a forecasting model which is capable to describing the natural reality. The strengths and shortcomings of existing deterministic prediction models and stochastic models were summarized. A coupled model with deterministic model and stochastic model was developed to forecasting groundwater level in Hengshui City, North Plain, China. The deterministic model was employed to describe groundwater flow characteristics and delineate performance of groundwater system. The neural network sequence predicting model was utilized to identify the stochastic factors including precipitation, evaporation and first kind of boundary condition and to predict their values in future. The coupled model was applied to forecast groundwater level regime which provided scientific results for controlling groundwater tables.

Key words: Hengshui groundwater system, deterministic model, stochastic model, improved BP neural network, coupled model of deterministic model and stochastic model, groundwater level prediction

INTRODUCTION

Groundwater which is the important part of water resources is important water supply resources in many cities within the north China and essential to the development of economy and society (Liu *et al*., 2008). In the recent 30 years, with the rapid development of economy and society, exploitation of groundwater are increasing greatly which induces a series of environmental problems and forms serious intimidate to the sustainable development of social economy in regional and local area (Daliakopoulos *et al*., 2005; Susilo *et al*., 2012). The fluctuation of groundwater level indicates that groundwater resources vary within a hydrogeologic unit or an area. Groundwater regime affected by natural and human activities reflects comprehensive multi inputs to groundwater system. Precipitation, evaporation, exploitation and etc are inputs to groundwater system, whereas, groundwater level variation is outputs to groundwater system. Groundwater level fluctuation is a complicated stochastic process. Various methods and models are employed to predict groundwater level (Yang *et al*., 2009). Regression analysis model is not applicable for long term prediction (Almedeij and Al-Ruwaih, 2006). The grey system model does not reflects Periodic and random of groundwater system. The exponential smoothing method is applicable for trends. Spectral analysis (Shih, 2009) is not suitable for the stochastic components accounted for the larger proportion. Artificial neural networks (Yoon *et al*., 2011), support vector machine (Yoon *et al*., 2011), genetic algorithm (Katsifarakis *et al*., 1999), chaos theory (Sun *et al*., 2010) and other nonlinear approaches (Shiri *et al*., 2013), do not describe groundwater flow, hydraulic properties and the interactions between groundwater system and its environment (Bidwell, 2005). Groundwater level forecasting research is grouped into deterministic and stochastic models in mathematic models. The solving approaches to deterministic models include analytic method, physical simulation and numerical simulation. The stochastic models comprises of regression analysis models, gray models, frequency analysis models, time series models and etc. (Maheswaran and Khosa, 2013). Groundwater regime

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research is complicated because complexity, nonlinear, multi-scales, mutability, randomicity and other essential attributes exist in groundwater system. It is significantly valuable to improve the accuracy and reliability of groundwater level prediction and develop a forecasting model which is capable to describing the natural reality.

The environmental geological problems occur frequently and seriously because of over-exploitation of groundwater in Heishui City, North Plain, China. A coupled model with deterministic model and stochastic model was developed to forecast groundwater level in Hengshui City.

HYDROGEOLOGY CONDITIONS

Aquifer system: The aquifer system was vertically divided into four aquifer named the first aquifer, the second aquifer, the third aquifer and the fourth aquifer. The bottom of the first aquifer of which the materials are alluvial muddy and sandy sediments occurs from 50-70 m depth. The aquifer comprises of medium sand or medium-fine sand appearing as banding. The thickness of sand covers a range from 15-30 m with less than 10 m in some local areas. The static water levels ranged from 2-12 me. The second aquifer materials derived from fluvial sandy sediments with a thickness ranging from 20-40 m. The bottom of the second aquifer is 150-180 m. This aquifer of which the bottom occurs from 250-270 m is connected with the first aquifer in the north-west. The third aquifer consisting of medium-fine sand associated with some coarse sand or fine sand derived from alluvial-diluvial sediments. The fourth aquifer of which the thickness is from 100-140 m consists of alluvial-diluvial and deltaic deposits. This bottom of this aquifer is from 450-600 m. In general, the first and second aquifers are merged into shallow groundwater system as phreatic-confined aquifer based on the similar hydrogeological characteristics. The confined third and fourth aquifers are combined into deep groundwater system due to the similar hydrogeological characteristics as well.

Groundwater recharge, flow and discharge: The recharge sources to shallow groundwater system are precipitation infiltration and irrigation return. The lateral flow is slow because of the plain landform and flat topography. The natural flow direction is towards from southwest to northeast associated with some variations due to groundwater exploitation. The main discharge pattern is groundwater pumping in the exploitation fresh water area while evaporation is the main discharge pattern in the saline groundwater area. The shallow groundwater system discharges to deep groundwater system.

The groundwater flowed from northwest to southeast naturally forty years ago. However, the Hengshui city is in lack of water resources, the deep groundwater has been overdrawn seriously. It has caused regional cone depression of deep groundwater in regional area. The current groundwater flow to groundwater cone depression. The lateral flow is very slowly in deep groundwater system.

The major groundwater discharge pattern is groundwater pumping.

CONCEPTUAL HYDROGEOLOGICAL MODEL

Model area and aquifers: The modeling area covers the main area with Heshui city district boundaries excluding southeast boundary (Fig. 1). The modeling aquifers included shallow groundwater system, deep groundwater system and the low permeable materials including silt and clay between shallow and deep groundwater system.

Hydraulic properties: The characteristics of groundwater cycle indicate that groundwater flow is three dimensional. Groundwater system in modeling accords with law of conservation of mass, the law of conservation of energy and Darcy's law. Groundwater exchange between shallow and deep groundwater system is evidence. The lithology and thickness of shallow and deep aquifers system varying spatially. The aquifer systems are heterogeneous and isotropy.

Boundaries:

- **Vertical boundaries:** The upper boundary is phreatic water table because water exchanges including infiltration, phreatic water evaporation and etc between shallow groundwater system and outside environment

  The lower boundary is the clays or mild clays which are low permeable layers with the thickness is over 15 m treated as impermeable boundary (Fig. 1)
- **Lateral boundaries:** The southeast boundary is treated as constant head boundary because there are many long term groundwater observation wells. The others are transformed into flux boundaries (Fig. 1).

DETERMINISTIC MODEL AND ITS SOLUATIONS

Determinstic model: The conceptual hydrogeological model was translated into heterogeneous, isotropy, three dimensional and transient groundwater flow model. The model was described as the following mathematical model.

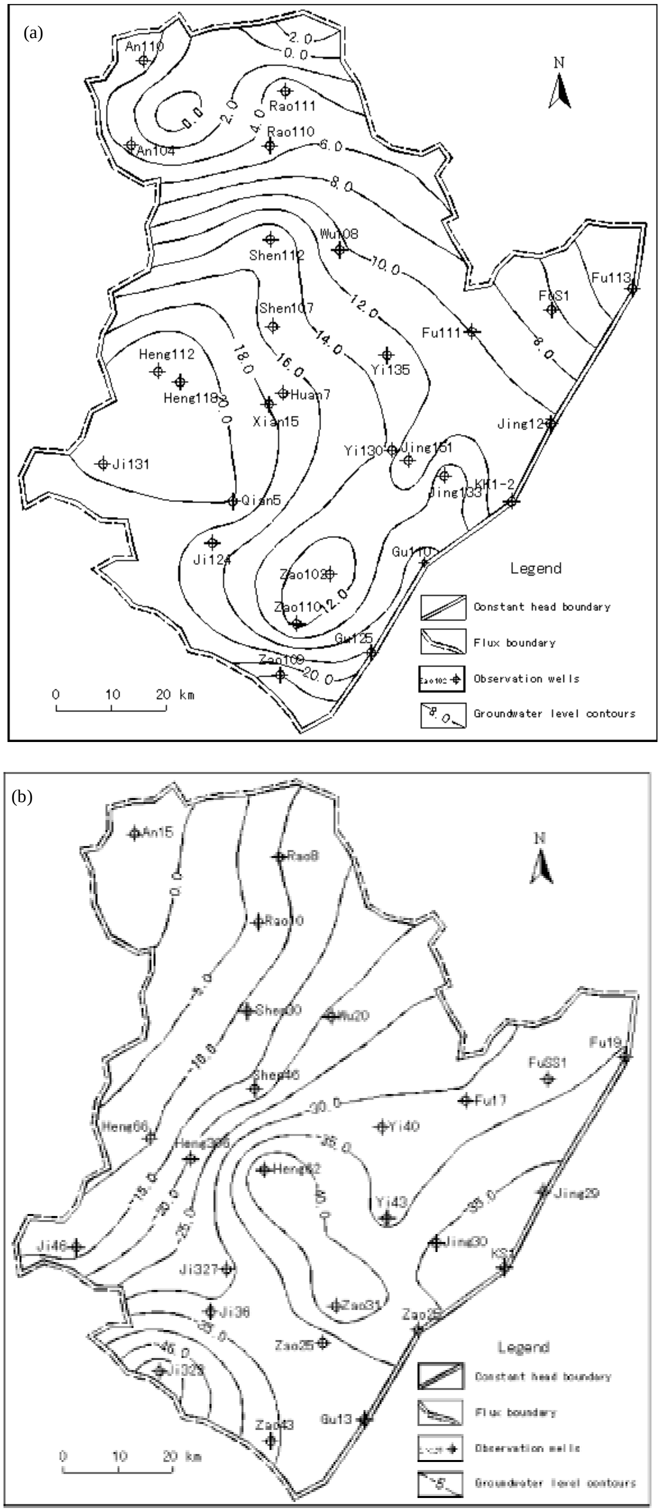

Fig. 1(a-b): Conceptual hydrogeological model of the shallow aquifer system (a) Deep aquifer system and (b) Aquifers

Solving the mathematic model: The mathematic model was developed with FEFLOW. The resultant mesh used in the modeling comprising of 10152 elements and 7112 nodes within the three layers. The initial hydrogeological parameters were determined from aquifer tests or published literature. Steady state condition was conducted to provide initial condition for the transient model of the flow field from Jan 30 to Dec 31, 2012.

Model calibration: The transient model was calibrated against the measured groundwater levels (Fig. 1) available from Jan 31 to Jun 30, 2012. The model was validated against the observed groundwater levels available from Jul 1 to Dec 31, 2012.

The observed vs. simulated water heads at all monitoring well locations and observation times is showed in Fig. 2. The comparison of model simulated results with the groundwater levels from different months and different locations does not reveal any large bias.

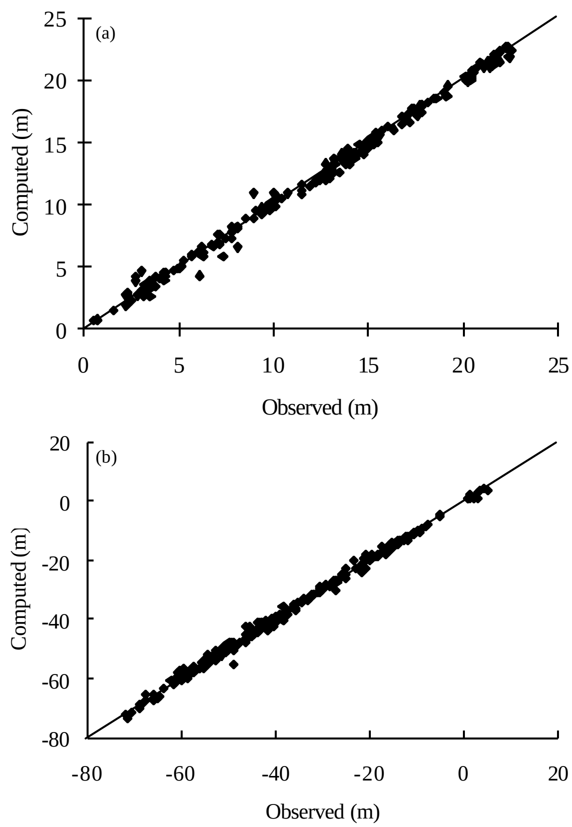

Fig. 2(a-b): Comparison between the observed and computed heads at all observation wells and times used in transient model calibration (a) For shallow groundwater and (b) For deep groundwater

Statistically, the mean errors between the measured and the computed groundwater levels for the 18 wells located in shallow aquifer system and 20 wells located in deep aquifer system at all observation times are -0.03 and 0.06 m, respectively. The mean absolute error for the observed and simulated groundwater levels of the shallow and deep aquifer systems are 0.31 and 0.88 m, respectively.

The Mean Error and Mean Absolute Error suggest that there were no significant global overcalculation or undercalculation in the model results. The RMSE (rooted mean squared error for the 18 and 20 wells data points are 0.43 and 1.19 m, indicating a reasonably robust match between the calculated and observed heads.

Examination of the temporal trends of the simulated heads as compared to that of measured heads, four observation wells selected from different the modeled area as shown in Fig. 1.

The calculated and observed groundwater hydrographs at the selected observation wells have similar trends (Fig. 3), with the simulated heads being in good agreement with the measured ones over 2012. Both graphic and statistics calibration results indicated that the deterministic model are believable and useful to quantify the future changes of groundwater resources in the study area.

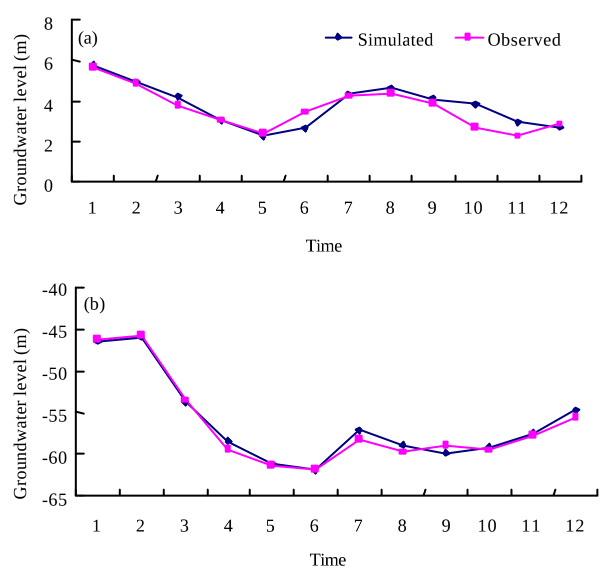

Fig. 3(a-b): Observed vs. computed groundwater level hydrographs at two specific observation wells (a) An110 well located in shallow aquifer system and (b) Heng 62 well located in deep aquifer system

STOCHASTIC MODELS

Precipitation, evaporation and constant head being stochastic factors to the groundwater system were solved to be forecasted in groundwater regime prediction.

BP neural networks: The BP (Back-Propagation) Neural Networks (here after BP) are used for prediction in many disciplines. BP was utilized to predict precipitation, evaporation and constant head.

The forecasting models of precipitation, evaporation and constant head are:

$$x_{n+k} = F_1(x_n, x_{n-1}, \cdots, x_{n-m}) \tag{1}$$

$$y_{n+k} = F_2(y_n, y_{n-1}, \cdots, y_{n-m}) \tag{2}$$

$$h_{n+k} = F_3(h_n, h_{n-1}, \cdots, h_{n-m}) \tag{3}$$

where, x_{n+k}, y_{n+k} and y_{n+k} are precipitation, evaporation and constant head time series.

$F_1(.)$ refers to function of the connections between the t+k moment precipitation with the t, t-1, t-2, Y,t-m moments precipitation; $F_2(.)$ Crefers to function of the connections between the t+k moment evaporation with the t, t-1, t-2, Y,t-m moments evaporation; $F_3(.)$ refers to function of the connections between the t+k moment constant heads with the t, t-1, t-2, Y,t-m moments constant heads. The BP was employed to approximate F_1, F_2 and F_3.

COUPLED MODEL

The numerical deterministic model and the stochastic models predicting precipitation, evaporation and constant head were merged into a coupled model as following E. 4:

$$A = \{h(t)\} = \{C\} \tag{4}$$

Where:

A = Ccoefficient matrix(matrix of coefficient of transmissibility [G] and matrix of coefficient of storage)[S^e])
{h(t)} = Water head matrix
{C} = Constant term

The numerical deterministic model and the stochastic models predicting precipitation, evaporation and constant head were merged into a coupled model as following:

$$\begin{cases} [A]\{h(t)\} = \{C\} \\ x_{n+k} = F_1(x_n, x_{n-1}, \cdots, x_{n-m}) \\ y_{n+k} = F_2(y_n, y_{n-1}, \cdots, y_{n-m}) \\ h_{n+k}|_{\Gamma_1} = F_3(h_n, h_{n-1}, \cdots, h_{n-m}) \\ \varepsilon_1 = \alpha \cdot x \\ \varepsilon_2 = G(y) \end{cases} \tag{5}$$

Where:

x = Cmonthly precipitation time series (mm)
y = Monthly evaporation time series (mm)
Γ_1 = Cconstant head boundary of the modeling domain
α = Cinfiltration coefficient of precipitation
G(y) = Cfunction of phreatic groundwater evaporation based on water surface evaporation

APPLICATION AND RESLUTS

Principles of groundwater prediction: The principles of groundwater prediction were determined based on the analysis geology, hydrogeology and groundwater usage:

- The prediction period is 18 years from 2013-2030. Characteristics of groundwater levels on each June 30 and December 31 in typical observation wells were analyzed
- An100 well located in fresh water area, Shen 112 well located in transition zone between middle saline to fresh water (TDS<1 g/L), Jing 133 well drilled in brackish water area (1 g/L = TDS<3 g/L and Xian 15 well located in saline water area (TDS = 3 g) were the typical observation wells drilled in shallow aquifer system. Heng 62 well, Ji322 well and Zao31 well located in deep aquifers in fresh water were typical observation wells for deep groundwater system
- Reducing the decline rate of groundwater level decline in deep groundwater system
- The plans of groundwater pumping were two kind of situations. One is maintaining the current groundwater usage, the other is groundwater pumping for meeting development of the economy and society
- The current quantities of deep groundwater pumping are 84109.2 H10^4 m^3 yr^{-1} including 73.25% of total groundwater pumping for irrigation. One H10^8 m^3 brackish groundwater instead of deep groundwater is pumped to mix with deep groundwater for irrigation in order to reduce the dependence of irrigation on deep groundwater from 2013-2030
- The total dissolved solids of irrigation is less than 1 g L^{-1} for irrigation

Groundwater pumping plans:

- **Plan one:** The exploitation of shallow groundwater in 2012 is 46520.3 H10^{4}m^3 including fresh water 44118.2 H10^{4}m^3 and brackish water 2402.1 H10^{4}m^3. The quantities of deep groundwater pumpage are 84109.2 H10^{4}m^3
- **Plan two:** The TDS of deep groundwater ranges from 267-743 mg L^{-1} with an average at 505 mg L^{-1}. Additional 1H10^{8}m^3 brackish water instead of 1H10^{8}m^3 deep groundwater is mixed with 5H10^8 m^3 deep groundwater for irrigation with TDS at 0.9 g L^{-1}
- **Plan three:** The pumpage of shallow groundwater, brackish water and deep groundwater are presented in Table 1
- **Plan four:** The pumping quantities of shallow groundwater, brackish water and deep groundwater are presented in Table 2. The brackish water is mixed with 5H10^8 m^3 fresh deep groundwater for irrigation

Groundwater levels prediction: The computed groundwater levels simulated by the coupled model on June 30 and December 31 of each year are analyzed for each plan.

Groundwater levels in shallow aquifer system: The variation of each typical observation wells located in shallow aquifer system are showed in Fig. 4a. Figure 4a showed that groundwater levels of each plan from high to low were plan 1, 3, 2 and 4, respectively. The overall groundwater levels declined from 2013-2030. The amplitude of groundwater level draw down in each well was different. The amplitude of groundwater level draw down of plan 1 was the smallest corresponding to what of plan 4 was the largest:

- **Fresh water area (TDS<1 g L^{-1}) (An 110 well):** Amplitudes of groundwater levels draw down corresponding to plan 1-4 were 16.19, 22.20, 20.27 and 26.36 m, respectively. The amplitude of plan 2 was 6.01 m larger than what of plan 1 because 1H10^{8}m^3 brackish water was pumped. Amplitude of plan 4 was 6.08 m larger than what of plan 3 because of the same reason above
- **Brackish water area (1≤TDS<3 g L^{-1}):** Amplitudes of groundwater declining corresponding to plan 1-4 were 7.75, 12.32, 12.50 and 17.14 m in typical observation well named Jing 133 because of overexploitation of brackish water.
- **Saline water area (TDS>3 g L^{-1}):** The amplitudes of plan 1-4 were 2.86, 3.31, 4.25 and 4.69 m of groundwater levels declining in typical observation well named Xian 15 well located saline water area mainly because of the water exchange between saline water area and fresh water area in shallow and deep aquifer system

Groundwater level dynamics in deep aquifers: Groundwater levels in typical observation wells decline

Table 1 Planed Exploitation quantities of groundwater of Plan three unit: 10^{4}m^3

Year	Deep groundwater	Shallow groundwater	Brackish water	Year	Deep groundwater	Shallow groundwater	Brackish water
2013	85322.1	44754.4	2436.7	2022	90987.0	47725.9	2598.5
2014	85887.1	45050.8	2452.9	2023	91760.6	48131.6	2620.6
2015	86482.7	45363.2	2469.9	2024	92588.5	48565.9	2644.3
2016	87111.2	45692.9	2487.8	2025	93475.3	49031.0	2669.6
2017	87775.4	46041.3	2506.8	2026	94425.8	49529.6	2696.7
2018	88478.3	46410.0	2526.9	2027	95445.4	50064.4	2725.9
2019	89223.1	46800.6	2548.2	2028	96540.0	50638.6	2757.1
2020	90013.2	47215.1	2570.7	2029	97715.9	51255.4	2790.7
2021	90263.5	47346.4	2577.9	2030	98980.0	51918.4	2826.8

Table 2 Planed Exploitation quantities of groundwater of Plan four and TDS of mixed water

Year	Deep groundwater (10^{4}m^3)	Shallow groundwater (10^{4}m^3)	Brackish water (10^{4}m^3)	TDS of mixed water (g L^{-1})	Year	Deep groundwater (10^{4}m^3)	Shallow groundwater (10^{4}m^3)	Brackish water (10^{4}m^3)	TDS of mixed water (g L^{-1})
2013	75322.1	44754.4	12436.7	0.902	2022	80987.0	47725.9	12598.5	0.907
2014	75887.1	45050.8	12452.9	0.903	2023	81760.6	48131.6	12620.6	0.907
2015	76482.7	45363.2	12469.9	0.903	2024	82588.5	48565.9	12644.3	0.908
2016	77111.2	45692.9	12487.8	0.904	2025	83475.3	49031.0	12669.6	0.908
2017	77775.4	46041.3	12506.8	0.904	2026	84425.8	49529.6	12696.7	0.909
2018	78478.3	46410.0	12526.9	0.905	2027	85445.4	50064.4	12725.9	0.910
2019	79223.1	46800.6	12548.2	0.905	2028	86540.0	50638.6	12757.1	0.911
2020	80013.2	47215.1	12570.7	0.906	2029	87715.9	51255.4	12790.7	0.911
2021	80263.5	47346.4	12577.9	0.906	2030	88980.0	51918.4	12826.8	0.912

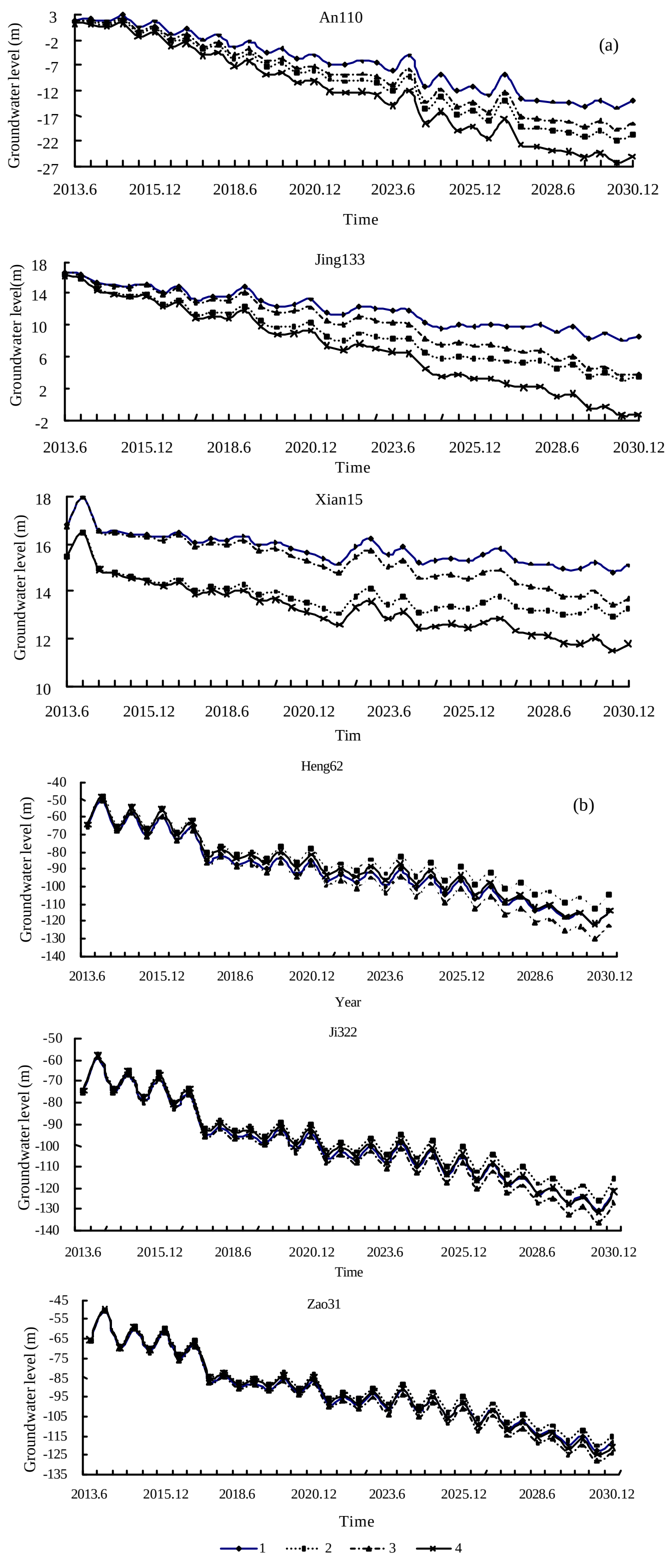

Fig. 4(a-b): Groundwater levels variation in typical observation wells of each plan (a) For shallow aquifer system and (b) For deep aquifer system. 1: Plan 1, 2: Plan 2, 3: Plan 3 and 4: Plan 4 with a high rate because of overexploitation in deep aquifer system for over 30 years (Fig. 4b). Groundwater levels corresponding to plan 2, 4, 1 and 3 are from high to low in the groundwater level hydrographs showed in Fig. 4b.

In general, groundwater levels corresponding plan 2 which met the irrigation and keep groundwater level

CONCLUSION

Deterministic and stochastic model of groundwater regime predicting is founded which is exploring a new method of groundwater regime predicting: In order to realize groundwater regime predicting, a series of neural network sequence prediction models are founded to forecast precipitation, evaporation and groundwater table of the first kind boundary. Neural network sequence prediction models are coupled with the identified and proved numerical model to forms the coupled model.

Groundwater exploitation case is brought forward to keep deep groundwater level from falling too much and too fast: Deterministic and stochastic model is used to forecast groundwater regime under the condition of four scheduled exploitation case of Hengshui city. Comparing with the forecasted results of each exploitation case and according to the rule of groundwater prediction, the second exploitation case is the best case. That is to say, regard the brackish water as the source of water utilization which is mixed with deep fresh water to be used in agriculture. Then not only meets the water need of agriculture, but also reduces recovery volume of deep groundwater which can efficiently keep deep groundwater table from falling too much and too fast.

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