Journal of Earth Science, Vol. 25, No. 6, p. 1033–1042, December 2014 *ISSN 1674-487X*
Printed in China
DOI: 10.1007/s12583-014-0493-8

Study on the Estimation of Groundwater Withdrawals Based on Groundwater Flow Modeling and Its Application in the North China Plain

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ABSTRACT: The amount of water withdrawn by wells is one of the quantitative variables that can be applied to estimate groundwater resources and further evaluate the human influence on groundwater systems. The accuracy for the calculation of the amount of water withdrawal significantly influences the regional groundwater resource evaluation and management. However, the decentralized groundwater pumping, inefficient management, measurement errors and uncertainties have resulted in considerable errors in the groundwater withdrawal estimation. In this study, to improve the estimation of the groundwater withdrawal, an innovative approach was proposed using an inversion method based on a regional groundwater flow numerical model, and this method was then applied in the North China Plain. The principle of the method was matching the simulated water levels with the observation ones by adjusting the amount of groundwater withdrawal. In addition, uncertainty analysis of hydraulic conductivity and specific yield for the estimation of the groundwater withdrawal was conducted. By using the proposed inversion method, the estimated annual average groundwater withdrawal was approximately 24.92×10^9 m^3 in the North China Plain from 2002 to 2008. The inversion method also significantly improved the simulation results for both hydrograph and the flow field. Results of the uncertainty analysis showed that the hydraulic conductivity was more sensitive to the inversion results than the specific yield.

KEY WORDS: inversion method, North China Plain, groundwater withdrawal, numerical modeling.

0 INTRODUCTION

The North China Plain (NCP) is an important economic center and agricultural region of the north part of China. The economic growth of this area has resulted in an increasing demand in water resources (Fang et al., 2010; Wang et al., 2007). Nevertheless, local surface water resources in the Haihe River Basin are not abundant, surface reservoirs have been built for most of the rivers in this region. This has led to a widespread surface water shortage across the NCP, thus, groundwater has been used as the major water resource for agriculture and industry. According to the results of the government statistical analysis, groundwater withdrawal accounts for around 69% of the total water resource supplied in this area (Sun et al., 2011; Hu et al., 2010; Zhang et al., 2009a). However, continuous over-pumping of groundwater has resulted in series of geological environmental and eco-environmental problems, including sustained water level decline, massive composite groundwater cones, groundwater resources depletion, and land subsidence. These environmental problems have threatened the water supply security and food safety of the local area (Yang et al., 2012; Alauddin and Quiggin, 2008; Hellegers et al., 2001). Therefore, the groundwater resource and associated environment problems in the NCP have drawn much attention and discussion in China and abroad (Pang et al., 2013; Li et al., 2012; Shi et al., 2011; Shen et al., 2009; Aji et al., 2008; Liu et al., 2008; Nakayama et al., 2006).

Groundwater pumping has been the main groundwater discharge in the NCP over the past decades. Understanding the current groundwater pumping situation and estimating the accurate amount of water exploited from the aquifers in the NCP will benefit the evaluation, development, and protection of groundwater resources. However, a number of factors, such as the non-uniform distribution of numerous pumping wells in the plain, the multiple supply purposes of groundwater resources, and the lack of a complete groundwater management, etc., have prevented the accurate measurement of the majority of agricultural pumping wells. Consequently, it's impossible to estimate accurate groundwater withdrawal data. In China, groundwater withdrawal is measured by some traditional methods, e.g., water metering and quota measurement (Liu et al., 2004). Though these methods are simple and practicable,

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Manuscript received May 13, 2014.
Manuscript accepted September 20, 2014.

Shao, J. L., Cui, Y. L., Hao, Q. C., et al., 2014. Study on the Estimation of Groundwater Withdrawals Based on Groundwater Flow Modeling and Its Application in the North China Plain. *Journal of Earth Science*, 25(6): 1033–1042. doi:10.1007/s12583-014-0493-8

the generated results usually have significant errors due to incomplete statistical analysis, inaccurate quota, and uncertainty in natural conditions; especially when these methods are applied to calculate the amount of water withdrawn for agricultural irrigation. Thus, an improved scientific method to estimate the groundwater withdrawal is greatly needed.

A great number of studies have focused on the groundwater withdrawal estimation. In arid or semiarid areas, groundwater resource provides the major water supply. Obtaining accurate information on the groundwater withdrawal is particularly critical for the investigation of the human influence on the regional generation of hydrological circulation (Kustu et al., 2010). In the early 1980s, Wray tried to estimate the groundwater withdrawal with the help of remote sensing (Wray, 1983). The United States Geological Survey also performed a groundwater withdrawal estimation of the Death Valley Basin from 1913 to 1998 by classifying the water resources consumption (Moreo et al., 2003). Other research efforts include Martinez-Santos and Martinez-Alfaro, who estimated the groundwater withdrawal of the agricultural areas in Central Spain (Martinez-Santos and Martinez-Alfaro, 2010), by coupling water table fluctuation method with groundwater balance equation; and Ruud et al., who established a GIS-based water balance model to solve the same problem (Ruud et al., 2004). In China, Wang and Wang proposed a fairly simple probability statistical method to calculate the groundwater withdrawal (Wang and Wang, 1999); and Sun et al. (2001) calculated the regional volume of groundwater withdrawal using a typical well- monitored system in combination with the actual power consumption measurements. Recently, Wu developed a power-consumption-per-machine method, however, the great errors in the calculated results were normally found for traditional methods comparing with the actual values (Wu, 2006). Xu et al. established a groundwater pumping equation (Xu et al., 2008). These studies on the estimation of the groundwater pumping did provide some solutions and improvements to overcome the disadvantages of the traditional methods, which either utilized the limited monitoring data or required a great amount of the groundwater withdrawal data.

Numerical modeling of groundwater flow has become an effective and useful way to investigate the hydrogeological systems and manage water resources. The progress in numerical modeling of ground water flow has been increasingly achieved according to the water balance principle, long-time sequences, and fairly complete groundwater monitoring data. Therefore, employing the groundwater models for the inversion of the groundwater withdrawal could be an alternative approach to provide more reasonable and accurate estimation of the groundwater withdrawal. Two typical algorithm packages, PEST (Omagbon and O'Sullivan, 2011) and UCODE (Eileen et al., 2005) coupling with MODFLOW are often used for the estimation of parameters. But for real parameter estimation problems, where there are a number of unknown parameters, this method always takes too much time to optimize them.

In this study, an inversion method for the estimation of groundwater withdrawal was proposed based on the groundwater numerical model. It estimated groundwater pumping rate by reducing the difference between observed groundwater levels and the simulated ones. To deal with a large number of pumping wells during the inversion procedure, the study area was divided into many subareas to replace these pumping wells, which could significantly save the computation time. In addition, the inversion method could decide the direction of inversion procedure according to the simulated groundwater levels instead of stochastic searching, which could get solution efficiently.

A synthetic case study was conducted to verify the feasibility and reliability of the inversion method. Finally, the NCP was chosen as an example to demonstrate the application of the inversion method. It showed the method had high efficiency in time under specified accuracy extent.

1 PRINCIPLE AND METHOD

1.1 Principle

According to the water balance principle, the relationship below exists for any groundwater system

$$Q_r - Q_d - Q_p = \mu^* \cdot A \cdot \frac{h_t - h_0}{\Delta t} \tag{1}$$

where Q_r, groundwater recharge in the mass balance area (L^3T^{-1}); Q_d, groundwater discharge in the mass balance area (L^3T^{-1}), excluding the groundwater withdrawal; Q_p, groundwater withdrawal (L^3T^{-1}); Δt, the period of the mass balance (T); A, area of the mass balance analysis (L^2); μ^*, specific yield of the aquifer (phreatic aquifer) or storage coefficient (confined aquifer); and h_0 and h_t are the average groundwater level at the beginning and the end of the balance period (L), respectively.

In groundwater simulation, the simulated groundwater levels may have certain deviations from the actual ones due to the inaccurate measurement of groundwater withdrawal. In other words, for the condition that the given groundwater withdrawal is less than the actual amount, the simulated groundwater level would be higher than the actual level, and vice versa. Based on the concept described above, the following balance equation can be established according to the given groundwater withdrawal in the model

$$Q_r - Q_d - Q_p' = \mu^* \cdot A \cdot \frac{h_t' - h_0}{\Delta t} \tag{2}$$

where Q_p', groundwater withdrawal given in the model (L^3T^{-1}); h_t', simulated average groundwater level at the end of the mass balance period for model calculation (L); other notations are the same as the ones described in Eq. (1).

Subtracting Eq. (1) by Eq. (2) gives

$$\Delta Q_p = \mu^* \cdot A \cdot \frac{\Delta h_t}{\Delta t} \tag{3}$$

where ΔQ_p, the volume of the groundwater withdrawal that needs to be adjusted based on the variations in groundwater level; Δh, difference between the actual and the simulated average groundwater levels at the end of the balance period (L), i.e., $\Delta h_t = h_t - h_t'$. Thus, the adjusted groundwater withdrawal will be

$$Q_p = Q_p^{'} - \Delta Q_p \tag{4}$$

From the above derivations, the estimated groundwater withdrawal is essentially more reasonable and accurate by the iterative calculation of groundwater modeling, which considers the differences between the actual groundwater levels and the simulated ones in each iteration step.

1.2 Estimation Method for the Groundwater Withdrawal

In this study, the groundwater flow model was used to estimate the groundwater withdrawal. For a regional groundwater modeling, in general, the groundwater withdrawal was treated as areal well pattern. The simulation area was divided into L pumping subareas according to the hydrogeological zones or administrative division, and the modeling grids corresponding to each of these subareas were determined. The simulation period can be divided into N pumping periods (stress periods). The procedure is described below (as shown in Fig. 1).

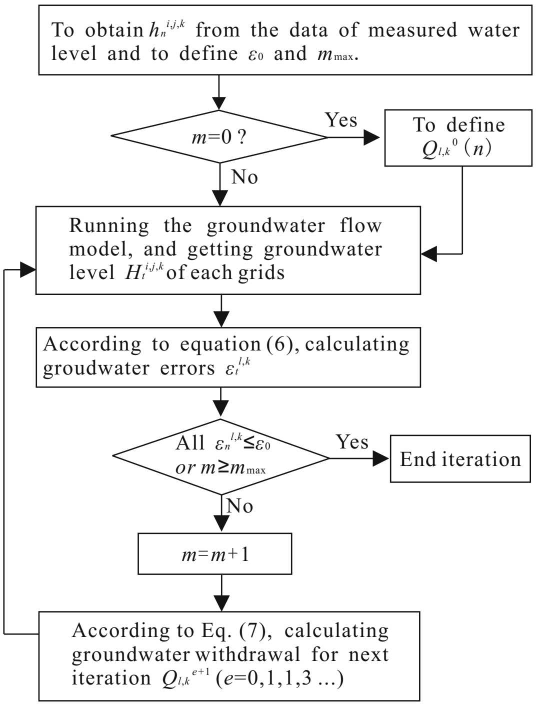

Figure 1. Flow chart of groundwater withdrawal inversion analysis.

(1) The Kriging interpolation method is used to obtain the measured water level of each grid in every pumping period, which serves as the initial level $h_0^{i,j,k}$ and fitting and correcting the water level $h_n^{i,j,k}$ (grid (i,j) in aquifer layer k in pumping period n). The standard error of the fitting groundwater level ε_0 and the maximum number of iterations $m_{\max}$ are presented.

(2) For an initial inversion calculation, the number of iterations is m=0 (m is the number of iterations, m=1, 2, 3…). The initial groundwater withdrawal of each layer in each pumping subarea $Q_{l,k}^{0}$ (n) (n=1,...,N) is determined using statistics and quota methods.

(3) Distribute calculated $Q_{l,k}^{m}(n)$ among the grids as the initial groundwater withdrawal and load into the model. Run the model with $h_0^{i,j,k}$ as the initial water level and derive the simulated groundwater levels in every pumping periods for each grid $H_n^{i,j,k}$ (grid (i, j) in aquifer layer k in pumping period n).

(4) Calculate the errors between the actual and the simulated average groundwater levels for each layer, pumping subarea, and pumping period.

$$\varepsilon_n^{l,k} = \frac{1}{N_l}\sum_{n=1}^{N_l}\left(h_n^{i,j,k} - H_n^{i,j,k}\right) \quad i,j \in l,\ \ l = 1,2,3,...,L \tag{5}$$

where l, number of the pumping subarea, l=1,2,...,L; N_l, number of the grids in pumping subarea l; and $\varepsilon_n^{l,k}$, error between the actual and the simulated average groundwater levels of layer k in pumping subarea l and pumping period n.

(5) If all calculated $\varepsilon_n^{l,k}$ values are less than ε_0, or iteration number m is greater than $m_{\max}$, the iteration procedure ends. Otherwise the iteration step continues.

(6) Calculate the volume of groundwater withdrawal that needs to be adjusted for the next iteration according to Eq. (6)

$$\Delta Q_{l,k}^{m}(n) = \mu_{l,k} \cdot A \cdot \varepsilon_n^{l,k} \tag{6}$$

where $\Delta Q_{l,k}^{m}(n)$, the volume of groundwater withdrawal in layer k that needs to be further adjusted for pumping subarea l and pumping period n after iterating m times (m^3/d); $\mu_{l,k}$, the average specific yield (phreatic aquifer) or storage coefficient (confined aquifer) of layer k in pumping subarea l; $\mu_{l,k} = \frac{1}{N_l}\sum_{n=1}^{N_l}\mu_{i,j,k}\ (i,j \in l,\ l = 1,2,3,....,L)$; the other notations are the same as above.

According to equations (4) and (6), the derived groundwater withdrawal for the next iteration $Q_{L,k}^{m+1}$ can be expressed as

$$Q_{l,k}^{m+1}(n) = Q_{l,k}^{m}(n) - \Delta Q_{l,k}^{m}(n) \quad i,j \in l,\ \ l = 1,2,3,...,L \tag{7}$$

repeat steps (3) to (6).

2 A SYNTHETIC CASE STUDY

2.1 Estimation of Groundwater Withdrawal

In order to evaluate the inversion method for groundwater withdrawal, a synthetic case study was conducted using an aquifer with a rectangular shape (10×10 km^2) (Fig. 2). The boundary conditions at the east and the west sides of the aquifer were assumed to be constant head of 100 m, while the others were assumed to be no flow boundaries. The designed aquifer was generalized as a homogeneous and isotropic one, with a hydraulic conductivity value of 50 m/d and a specific yield value of 0.15. The surface elevation and the bottom elevation of the designed aquifer were 115 and 50 m, respectively. The spatial domain was discretized into 10 000 girds with a grid size of 100×100 m^2. The initial water level of the aquifer was 100 m.

We assumed that there were 100 square pumping subareas in the study area (as shown in Fig. 2), the real pumping rates of subarea (3, 4) and subarea (7, 6) are shown in Table 1, and the groundwater pumping rates in the other subareas are zero.

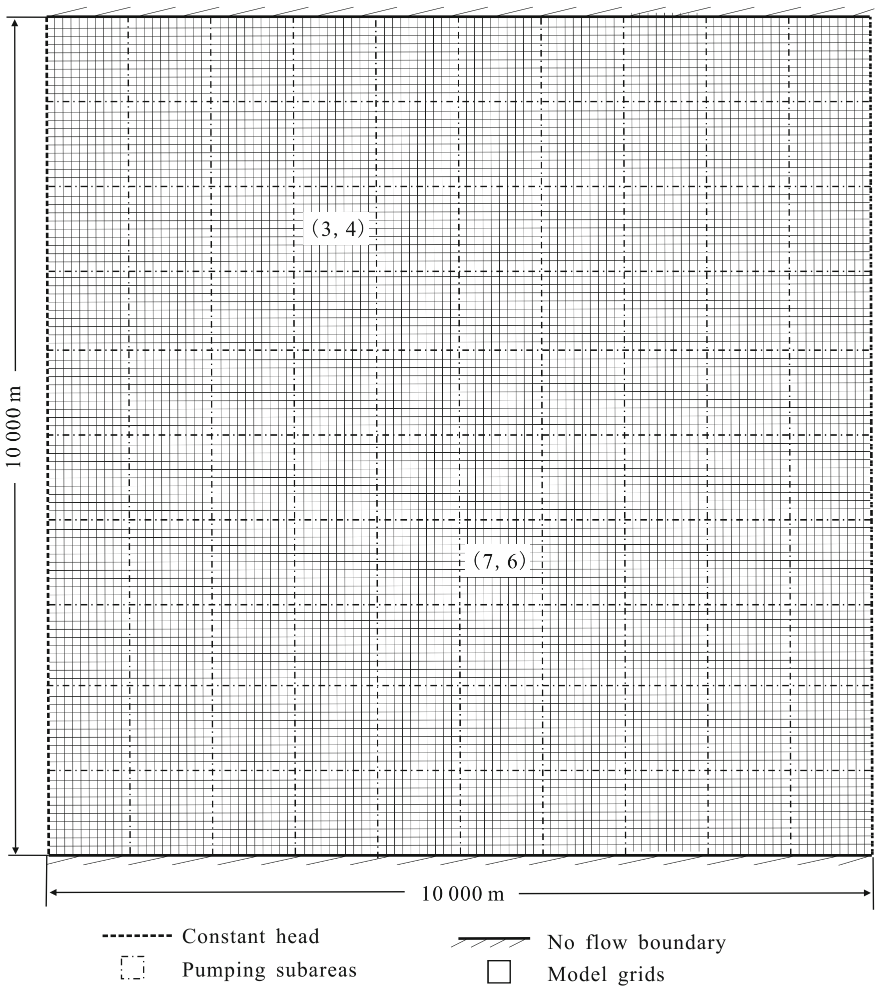

Figure 2. Synthetic case study area.

Table 1 Estimated groundwater withdrawal and errors (ε_0=0.1 m)

Years		1	2	3	4	5	6	7	8	9	10	Average
Subarea (3, 4)	RPR	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
	EPR	51.90	48.82	48.73	48.83	48.87	48.84	49.2	49.01	49.31	49.08	49.26
	Errors (%)	3.82	-2.35	-2.53	-2.32	-2.26	-2.30	-1.57	-1.98	-1.38	-1.83	1.47
Subarea (7, 6)	RPR	50.00	70.00	90.00	60.00	40.00	20.00	50.00	70.00	90.00	100.00	64.00
	EPR	48.23	69.75	88.59	59.26	39.19	18.93	49.04	69.01	89.1	98.96	63.01
	Errors (%)	-3.53	-0.35	-1.56	-1.23	-2.02	-5.33	-1.91	-1.40	-1.00	-1.03	-1.54

RPR. Real Pumping rate (m^3/d); EPR. estimated pumping rate (m^3/d).

Table 2 Estimated groundwater withdrawal and errors (ε_0=0.01 m)

Years		1	2	3	4	5	6	7	8	9	10	Average
Subarea (3, 4)	RPR	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
	EPR	50.19	50.01	49.90	49.93	49.89	50.17	49.83	49.89	49.92	49.90	49.97
	Errors (%)	0.39	0.04	-0.18	-0.14	-0.20	0.35	-0.33	-0.20	-0.15	-0.20	-0.06
Subarea (7, 6)	RPR	50.00	70.00	90.00	60.00	40.00	20.00	50.00	70.00	90.00	100.00	64.00
	EPR	49.82	69.96	89.94	59.86	39.8	20.19	49.82	69.86	89.89	99.91	63.92
	Errors (%)	-0.35	-0.05	-0.07	-0.23	-0.32	0.97	-0.35	-0.19	-0.12	-0.08	-0.13

RPR. Real pumping rate (m^3/d); EPR. estimated pumping rate (m^3/d).

In the beginning, the model was run for 10 years at the real pumping rate given above, and then the groundwater levels at each grid can be calculated. Using the simulated groundwater levels as the standard values, the groundwater pumping rate for each subarea could be estimated based on the inversion method. Table 1 and Table 2 show the results within two different precisions. With a precision ε_0 value of 0.1 m, the average error over 10 years was 1.47% for the subarea (3, 4), and was 1.54% for the subarea (7, 6). The errors for all stress periods ranged from 1.00% to 5.33%. Moreover, the accuracy of the estimated results can be improved with a decrease in precision value ε_0 from 0.1 to 0.01 m. Under such conditions, the average errors over 10 years for the subarea (3, 4) and subarea (7, 6) were 0.06% and 0.13%, respectively. In general, the higher precision was applied, the more accurate estimated results could be obtained.

Figure 3 shows the observed groundwater levels and the estimated groundwater levels for two different precisions. With a precision value of 0.1 m, the simulated groundwater levels have slight differences with the real ones. In particular, when the precision was improved to 0.01 m, there was almost no difference between the real groundwater levels and the simulated ones. The same situation could also be found in the groundwater time series of observation wells (Fig. 4), which were installed in the center of these two pumping areas in the model.

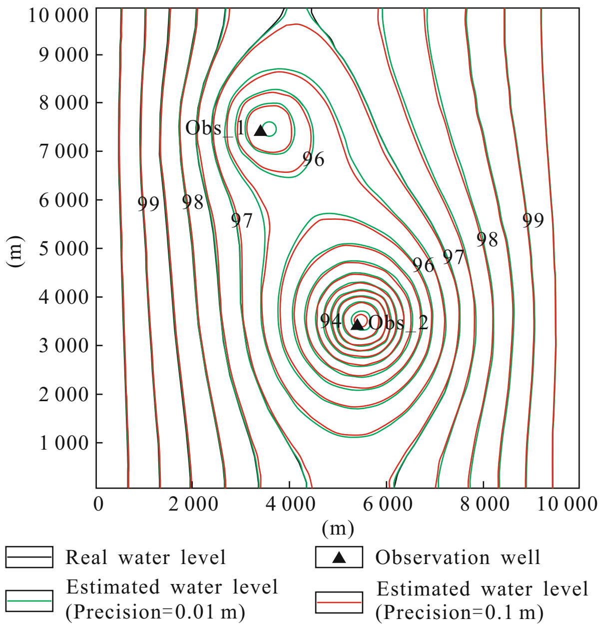

Figure 3. Fitting map of the real and the estimated water levels at the end of the simulation period.

2.2 Uncertainty Analysis

The evaluation of the inversion method discussed above is based on the assumption that all the other hydrogeological parameters and mass balance items are already given and are relatively certain. However, in field study, there is a lot of uncertainty in hydrological factors (for example, hydrological parameters), which often affects the reliability of the inversion method. Therefore, it is necessary to present the uncertainty analysis for this inversion method. As an example, the uncertainty analysis was conducted on hydrogeologic parameters, such as hydraulic conductivity and specific yield. The uncertainty analysis equation can be expressed as

$$\lambda_\alpha = \frac{\partial Q}{\partial \alpha} \tag{8}$$

where α, uncertainty factor; Q, estimated groundwater withdrawal using the above method; λ_α, sensitive index of estimated groundwater withdrawal Q for the uncertainty factor α.

In the inversion model, hydraulic conductivity K_0 of 50 m/d and specific yield μ_0 of 0.15 were set as the 'standard' parameters, and then Q_0 would be obtained after running the model. The parameters were adjusted to some extent in the model and the corresponding ground water withdrawal Q could be obtained. To simplify the analysis, the parameters were converted into dimensionless indices

$$\begin{cases} \alpha_K = \dfrac{K-K_0}{K_0} \times 100\% \\ \alpha_\mu = \dfrac{\mu-\mu_0}{\mu_0} \times 100\% \\ q = \dfrac{Q-Q_0}{Q_0} \times 100\% \end{cases} \tag{9}$$

Table 3 and Table 4 present the results from the inversion model and dimensionless indices. The tables and Fig. 5 demonstrate that the estimated groundwater withdrawal is more sensitive to hydraulic conductivity than specific yield. As the variation of hydraulic conductivity increases, the error of estimated pumping rate increases to the similar extent, and the average sensitive index (gradient) λ_K is 0.87. However, as the

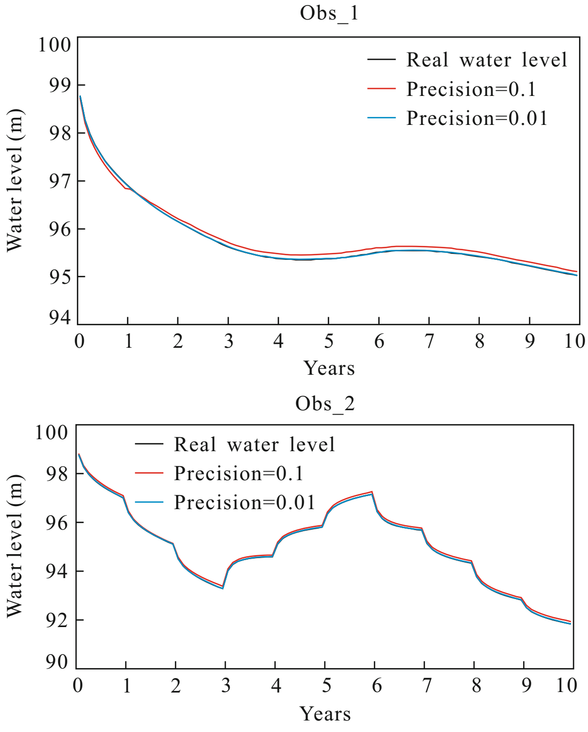

Figure 4. The fitting curves of the groundwater level in two observation wells.

Table 3 Uncertainty analysis results of subarea (3, 4) for hydraulic conductivity (ε_0=0.1 m)

K	25.00	30.00	35.00	40.00	45.00	50.00	55.00	60.00	65.00	70.00	75.00
RPR	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
EPR	27.31	31.69	36.10	40.38	44.63	49.26	53.40	57.70	62.05	66.40	70.85
q_K (%)	-45.38	-36.62	-27.80	-19.24	-10.74	-1.48	6.80	15.40	24.10	32.80	41.70
α_K (%)	-50.00	-40.00	-30.00	-20.00	-10.00	0.00	10.00	20.00	30.00	40.00	50.00
$\bar{\lambda}_K$	0.87										

K. Hydraulic conductivity (m/d); $\bar{\lambda}_K$. average gradient between estimated groundwater rate and hydraulic conductivity with dimensionless indices.

Table 4 Uncertainty analysis results of subarea (3, 4) for specific yield (ε_0=0.1 m)

μ	0.07	0.09	0.11	0.13	0.15	0.17	0.19	0.21	0.23
RPR	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
EPR	46.24	46.83	47.56	48.26	49.26	49.73	50.56	51.29	52.14
q_μ (%)	-7.52	-6.34	-4.88	-3.48	-1.48	-0.54	1.12	2.58	4.28
α_μ (%)	-53.33	-40.00	-26.67	-13.33	0.00	13.33	26.67	40.00	53.33
$\bar{\lambda}_\mu$	0.11								

μ. Specific yield; $\bar{\lambda}_\mu$. average gradient between estimated groundwater rate and specific yield with dimensionless indices.

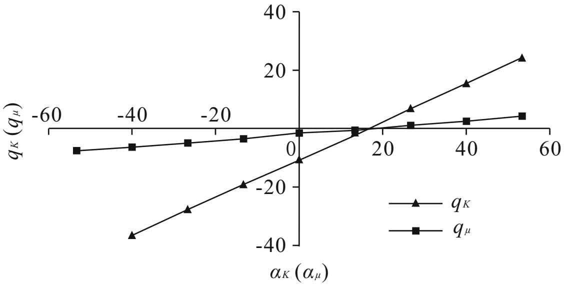

Figure 5. The curves of change rates of estimated groundwater withdrawal (q) with the rates of hydraulic conductivity α_K and specific yield α_μ.

value of specific yield varies, the estimation error in the pumping rate is much moderate, and the generated average sensitive index λ_μ is 0.11. It indicates that the precision of hydraulic conductivity is more important. If the precision is greater than 80%, the error of the estimated groundwater withdrawal would be less than 20%. Therefore, the precision of the hydraulic parameters of the aquifer is critical to obtain an accurate estimation of groundwater withdrawal using the inversion method. Especially, hydrogeologists should try their best to improve the precision of hydraulic conductivity.

3 ESTIMATION OF GROUNDWATER WITHDRAWALS IN THE NORTH CHINA PLIAN

3.1 Hydrogeology and Groundwater Development

The NCP lies in the eastern part of China, and extends from Mount Yanshan in the north to the Yellow River in the south, the Bohai Sea in the east and the Mount Taihang in the west. The NCP covers plain areas of Beijing, Tianjin, Hebei Province, and those to the north of the Yellow River in Henan and Shandong provinces (as shown in Fig. 6) with an area of 139×10^3 km^2. The Yellow River runs through the southern and southeastern margins of the study area.

Horizontally, the NCP has a layer of sediment with a thickness of 300–500 m, typically comprising of alluvial-proluvial, fluvial-lacustrine, and marine facies from the west to the east. Vertically, the aquifer systems in the study area are traditionally divided into four hydrogeologic layers. Aquifer I is phreatic layer which has a floor approximately 10–60 m

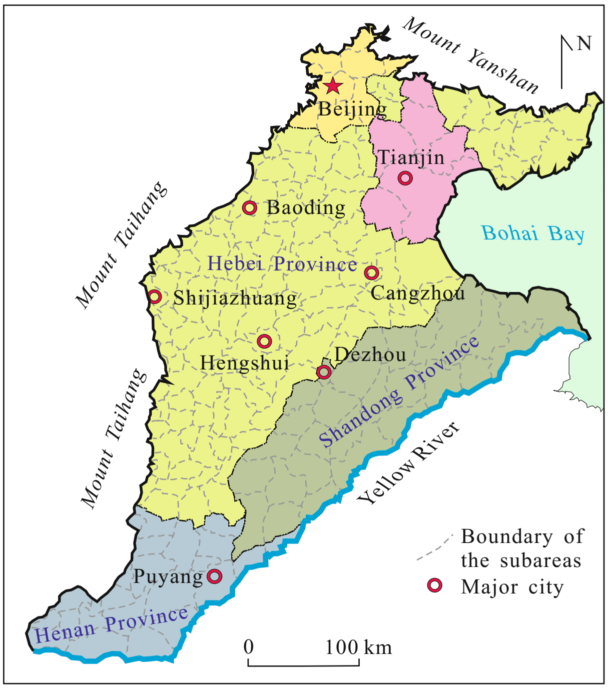

Figure 6. Geography location of the North China Plain and spatial distributions of 181 groundwater pumping subareas for groundwater withdrawal inversion analysis.

deep and comprises of pebble, gravel and sands. Aquifer II locates roughly 120–270 m deep and comprises of gravel and medium coarse sand, which features with high water abundance. The floors of aquifers III and IV are approximately 250–350 and 550–650 m deep, respectively, which comprise of medium to silt sand. The aquifers II, III, and IV are defined as confined ones. Aquifer I normally has a close hydraulic connection with the aquifer II, thus, aquifer II normally merges with aquifer I.

The groundwater in the NCP is primarily recharged by precipitation infiltration, followed by lateral inflow from piedmont, streams, and a smaller extent from channel seepage, agricultural irrigation leakage and the leakage of the karst water concealed. Under natural condition, the groundwater discharges typically in the forms of spring overflow, phreatic water evaporation, and lateral outflow. However, in the recent decades, groundwater pumping has already been the principal way of groundwater discharge. The groundwater in this area is characterized with an intensive recharge in the rainy season and a discharge/depletion throughout the years.

In the NCP, extensive groundwater pumping started from the 1960s. With the development of industry and agriculture, the areas with groundwater pumping have been enlarged and the amount of groundwater withdrawal has been significantly increased. A combined shallow-deep pumping pattern has formed. The mean annual groundwater withdrawal in this area increased from less than 5.0×10^9 m^3 in the 1960s to more than 10.0×10^9 m^3 in the 1970s. From 1980 to the end of the 20th century, the mean annual groundwater withdrawal exceeded 20.0×10^9 m^3. After the year 2000, the groundwater withdrawal started decreasing in some areas (e.g., Tianjin and Hebei Province) as people gradually realized the environmental hazard caused by excessive groundwater pumping. For some individual areas, the amount of groundwater withdrawal still kept steady (Wu et al., 2010).

Based on Zhang et al.'s results, regarding to the sustainable utilization of groundwater resources in the NCP, groundwater pumping is principally from the shallow aquifers (Zhang et al., 2009b). In 2003, for instance, the water withdrawal from the shallow groundwater aquifers accounted for about 85.71% of the total amount of ground water withdrawn, and pumping wells were typically located in and around the alluvial-proluvial fans. The water from deep groundwater pumping accounted for about 14.29%, and the associated pumping wells typically located in the fluvial-lacustrine plains in the east.

Since the NCP is one of the most important agricultural areas in China, irrigation water usage takes the largest proportion of the groundwater utilization in the area, approximately 77.31% of the total amount of groundwater withdrawal. In some big cities, including Beijing, Tianjin, Shijiazhuang, and Cangzhou, groundwater pumping are more intensive than the other areas (i.e., up to 400×10^3 m^3/a·km^2).

3.2 Numerical Modeling of Groundwater

Based on the three-dimensional groundwater flow model of the NCP by Shao et al. (Shao et al., 2013, 2009), Li et al. (2013) improved the model by prolonging the simulation period and refining the spatial cells. In the improved model, the simulation period was extended from 2 years (2002–2003) to 7 years (2002–2008), and the size of the simulation cell was decreased to 1 000 m×1 000 m. The model was calibrated using the hydrographs from 101 observation wells and the groundwater contours, which were obtained by groundwater level monitoring in the NCP. Groundwater withdrawal inversion was the primary and critical step of the model calibration, in which the hydrogeological parameters, e.g., hydraulic conductivity and specific yield of unconfined aquifer as well as specific storage of confined aquifer, were adjusted using the trial-and-error method.

3.3 Results and Analysis for the Estimation of Groundwater Withdrawals

Using the above estimation method and running the groundwater flow model of the NCP, groundwater withdrawals were estimated. As shown in Fig. 5, the uncertainty of the hydrogeological parameters does affect the estimation of the groundwater withdrawals. However, in the past fifty years, a large amount of research has been conducted on the hydrogeological parameters in the NCP (Zhang et al., 2009a), the parameters in this study were determined based on the summary of the results of the former studies, and these parameters are certain and in very good accuracy. Therefore, the uncertainty of the parameters in the NCP on the effect of the groundwater withdrawals can be neglected. Table 5 shows the estimated groundwater withdrawal of the shallow layers (aquifers I and II) and the deep layers (aquifers III and IV) in the NCP. The annual average groundwater withdrawal of the years 2002–2008 was 24.92×10^9 m^3, and the estimated groundwater withdrawal was to some extent different from the measured withdrawal, especially in the shallow layers. The estimated groundwater withdrawal values were greater than the measured ones, which can be explained as the following.

The regional annual precipitation of the NCP from 2002–2008 showed that the plain had a gradual decrease in the

Table 5 Estimated and measured groundwater withdrawal in the North China Plain from 2002 to 2008 (10^9 m^3)

Time (year)		2002	2003	2004	2005	2006	2007	2008
Shallow	Measured	20.426	19.605	20.426	19.605	20.426	19.605	20.426
	Estimated	20.643	19.698	22.903	23.331	21.994	20.814	20.342
Deep	Measured	3.334	3.285	3.334	3.285	3.334	3.285	3.334
	Estimated	3.417	3.378	3.871	4.359	3.193	3.172	3.322
Estimated total withdrawals		24.060	23.076	26.774	27.690	25.187	23.986	23.664
Annual precipitation (mm)		360.957	653.691	582.629	530.022	438.537	495.571	560.460

precipitation from 2003 to 2005, and the precipitation reached the minimum in 2005. Under such circumstance, to meet the industrial and agricultural water demands in the NCP, it was very necessary to increase the amount of groundwater withdrawal and thus resulted in higher estimated groundwater withdrawals. (2) Since the NCP has a relative large area, the measurements of the groundwater withdrawal in some individual districts or counties may be incomplete and inaccurate. Especially, the NCP is an agriculture area where agricultural irrigation wells are widely distributed. Many of the groundwater pumping wells can be easily neglected and thereby the measured amounts of groundwater withdrawal are less than the real ones.

The inversion method for groundwater withdrawal analysis estimates the amount of groundwater withdrawal by comparing the simulated levels with the actual ones, and further to derive the differences in water levels. When the simulated levels are higher than the actual levels, the groundwater withdrawal is increased. Otherwise, the withdrawal is reduced. Thus, for an area where the level difference is highly variable, the peak-clipping-for-valley process may often lead to a difference between the measured and the actual groundwater withdrawal.

Figure 7 shows the fitted shallow groundwater flow field in the NCP. The simulated water levels in the mountain front area after the inversion process are significantly higher than the ones under the initial condition, and the simulated water levels are roughly the same as the actual water levels. While the deep groundwater flow field has little change after the inversion process, because the flow field has shown a good fitting before the inversion process. Groundwater flow in the central plain area does not show a noticeable overall trend, and this is basically reflected in the simulated flow field. In the east coastal area, the simulated shallow groundwater flow presents a noticeable SW to NE trend, and this is also the same as the overall flow direction of the actual flow field. In a word, the application of the groundwater withdrawal inversion procedure improves the fitting results of the flow fields.

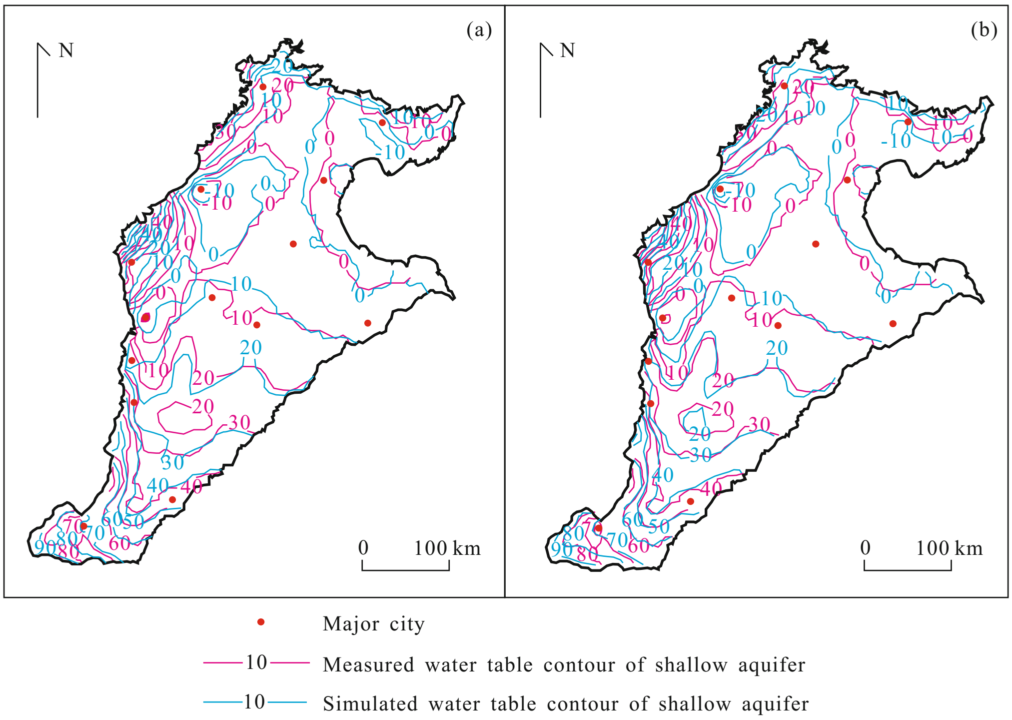

Figure 7. Fitted shallow groundwater flow fields of the North China Plain in June 2008 (a) before the inversion procedure, and (b) after the inversion procedure.

4 DISCUSSION

In this study, the groundwater withdrawal in the NCP was estimated by establishing a groundwater flow model. The principles of the proposed inversion method are water balance and the hydrogeological characteristics of the study area that are taken into account in the model. This method can be applied to obtain more accurate groundwater withdrawal data than the traditional statistical methods, and this method to some extent avoids the disturbance of external factors to data statistics. However, there are also some deficiencies in this study, owing to both the groundwater flow modeling and the collection of research data.

Firstly, because this study was based upon the existing groundwater flow modeling in the NCP, the accuracy of the groundwater withdrawal from the inversion procedure was inevitably subject to the accuracy of the parameters and recharge/discharge terms used in the model. With this respect, high-accuracy hydrogeological survey, full-scale groundwater data monitoring, and suitable model conceptualization and accurate calibration are not only prerequisites for better simulating groundwater system in the study area, but also the basis for subsequent research, such as groundwater withdrawal estimation. Therefore, it is necessary to further improve the model accuracy in the future study.

Secondly, the groundwater withdrawal of the NCP was estimated using the groundwater level data. Due to the lack of the groundwater level data of consecutive years, the accuracy of the inversion procedure was apparently limited. Therefore, it is important to collect more hydrogeologic survey data, especially the groundwater level monitoring data.

Lastly, as mentioned above, this inversion procedure was based on the measured groundwater withdrawal data of the years 2002 and 2003. Further work is still needed to verify and compare the inversion results based on the measured groundwater withdrawal data of consecutive years.

In addition to overcome the deficiencies in the study described above, researchers may also try the following to improve the inversion method: (1) using sufficient precipitation data, the estimated groundwater withdrawal could be distributed non-uniformly according to the regional precipitation characteristics of the study area; (2) conducting intensive studies on the groundwater withdrawal inversion method, for example, optimization method; (3) distributing the estimated total groundwater withdrawal among the water consumptions of different sectors in a rational way according to the seasonality and proportions of the different water consumptions, e.g., agriculture, municipal and industry; and (4) conducting some uncertainty analysis to further demonstrate the reliability of the inversion method for real work.

5 SUMMARY AND CONCLUSION

Groundwater withdrawal is an essential quantity for groundwater resource evaluation and management, however, groundwater withdrawal is very difficult to be accurately measured. In this study, an inversion method was proposed to estimate groundwater withdrawal. The inversion method was based on the water balance principle, and it estimated groundwater withdrawal by fitting the simulated groundwater levels with the observed ones using a well calibrated groundwater flow model. To assess the reliability of the inversion method, a synthetic case study was conducted. The simulation result indicated that the inversion method could obtain accurate estimation of the pumping rate. In addition, the uncertainty analysis results showed that hydraulic conductivity was more sensitive to the inversion results than the specific yield.

The proposed inversion method was applied in the NCP based on the numerical modeling of groundwater flow. The numerical modeling of groundwater flow of this area was developed based on the models established in the previous works. The modeling cell size was refined to 1 000 m×1 000 m and the simulation period was prolonged to the years 2002–2008. By adjusting the water withdrawal to match the simulated and observed water levels, the groundwater withdrawals of period 2002–2008 in the NCP was estimated. The inversion results showed that the estimated average groundwater withdrawal was 24.92×10^9 m^3 per year, which was to some extent different from the measured one, especially in the shallow layers. Meanwhile, the inversion procedure also improved the fittings for groundwater flow fields in the NCP.

ACKNOWLEDGMENTS

This study was supported by the National Basic Research Program of China (No. 2010CB428804) and the Public Welfare Industry Special Funds for Scientific Research from Ministry of Land and Resources of China (No. 201211079-4). The authors are grateful to the staff of the Institute of Hydrogeology and Environmental Geology, Beijing Institute of Geological Survey, Tianjin Institute of Geological Survey, Hebei Institute of Geological Survey, Henan Institute of Geological Survey, Shandong Institute of Geological Survey and Tianjin Geological Survey Center for their great help during the research.

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