Groundwater Flow Simulation and its Application in Groundwater Resource Evaluation in the North China Plain, China

SHAO Jingli[1,*], LI Ling[1], CUI Yali[1] and ZHANG Zhaoji[2]

1 School of Water Resources and Environment, China University of Geosciences, Beijing 100083, China
2 The Institute of Hydrogeology and Environmental Geology, CAGS, Shijiazhuang 050061, China

Abstract: The purpose of this study is to establish a 3D groundwater flow modelling for evaluating groundwater resources of the North China Plain. First, the North China Plain was divided into three aquifers vertically through a characterization of hydrogeological conditions. Groundwater model software GMS was used for modeling to divide the area of simulation into a regular network of 164 rows and 148 lines. This model was verified through fitting of the observed and the simulated groundwater flow fields at deep and shallow layers and comparison between the observed and simulated hydrographs at 64 typical observation wells. Furthermore, water budget analysis was also performed during the simulation period (2002-2003). Results of the established groundwater flow model showed that the average annual groundwater recharge of the North China Plain during 1991 to 2003 was 256.68×10^8 m^3/yr with safe yield of groundwater resources up to 213.49×10^8 m^3/yr, in which safe yield of shallow groundwater and that of deep groundwater was up to 191.65×10^8 m^3/yr and 22.64×10^8 m^3/yr respectively. Finally, this model was integrated with proposal for groundwater withdrawal in the study area after commencement of water supply by South-North Water Transfer Project, aiming to predict the changing trend of groundwater regime. As indicated by prediction results, South-North Water Transfer Project, which is favorable for effective control of expansion and intensification of existing depression cone, would play a positive role in alleviation of short supply of groundwater in the North China Plain as well as maintenance and protection of groundwater.

Keywords: groundwater, model, groundwater recharge, safe yield, South-North Water Transfer Project, North China Plain

1 Introduction

The North China Plain is located in the eastern part of China (Figure 1), which borders on Taihang Mountain, Yanshan Mountain and Yellow River to the west, north and south respectively, covering a total area of 13.90×10^4 km^2. In the early 1950s, groundwater resources in the North China Plain were abundant, characterized by extensive distribution and shallow burying depth (Zhang, 2005). However, along with the impact of change of global climate and human activity, corresponding changes (Wang et al., 2009) have taken place to groundwater regime in this area. As a result, the groundwater resources are gradually in short supply due to uncontrolled exploitation (Liu et al., 2001). According to statistics (Zheng et al., 2010), the percentage of groundwater supply in the North China Plain has reached 70% of the total in this area in recent years. Due to long-term excessive pumping, groundwater resources in local regions are in a trend of exhaustion. Moreover, some negative effects caused by groundwater depletion like land subsidence and deterioration of water quality also have serious impact on the safety of water and grain supply in this area (Zhang et al., 2009; Xia, 2002; Ma et al., 2011). Therefore, establishment of regional groundwater model in the North China Plain has a practical significance to the quantitative evaluation of groundwater resources and long-term prediction of groundwater regime in this area.

Normally, the regional groundwater model refers to a model at the level of basin, drainage area or larger administrative area, which is used for evaluation, forecasting and scientific management of regional groundwater, as well as study of groundwater circulation. This scientific method has attracted much attention ever since it was put forward. Meanwhile, a series of scientific

* Corresponding author. E-mail: jshao@cugb.edu.cn

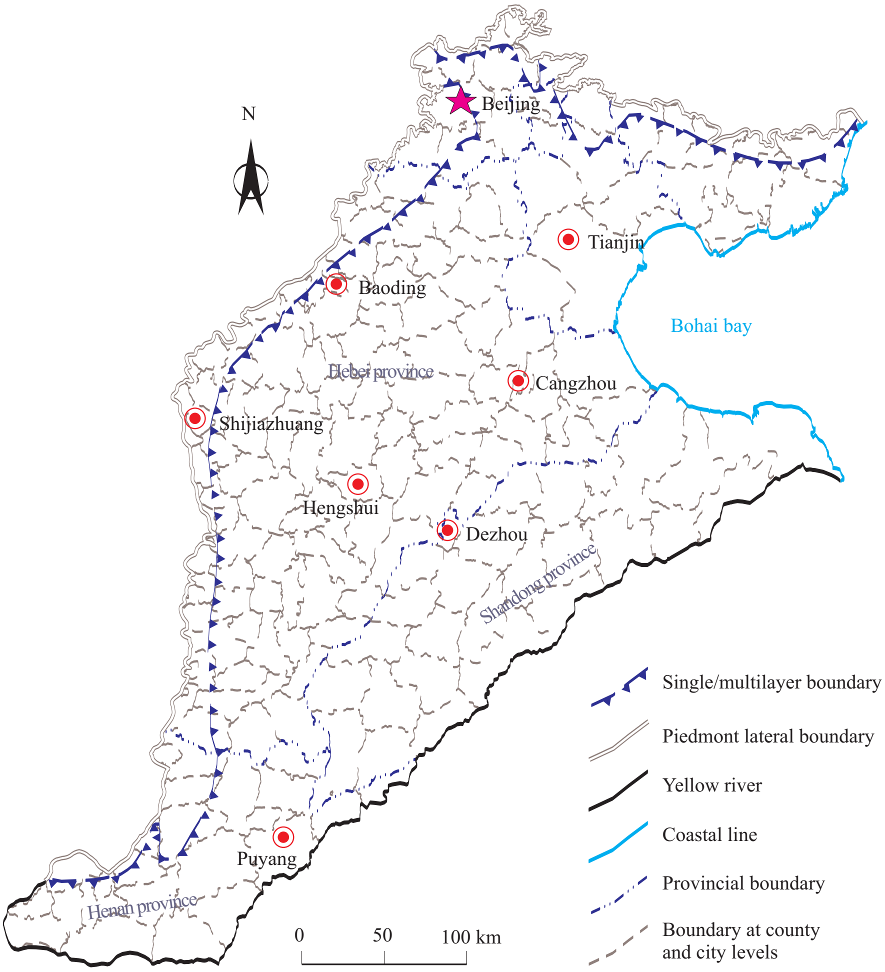

Fig. 1. Domain and boundaries of the North China Plain.

particular, the United States Geological Survey carried out a simulation of regional groundwater flow at Death Valley for the purpose of study and experiment of the migration of relevant substance in groundwater. Based on this numerical model, a number of steady flow (D'Agnese et al., 2002) and transient flow (Belcher, 2004) models were developed with the help of MOFLOW with the coverage of simulation area up to 5×10^4 km^2. Moreover, the United States Geological Survey also performed such tasks as the study of evapotranspiration of regional groundwater (DeMeo et al., 2003) and inversion of groundwater pumping for the period from 1913 to 1998 (Moreo et al., 2003). In China, the hydrogeologists began to attach high importance to the study of regional groundwater flow model from the late 1990s. This is typically represented by the Survey and Evaluation of Groundwater Resources in Major Basins in North China as organized by China Geological Survey from 2003 to 2005. Some regional groundwater flow models have been established in major basins in North China through implementation of this project. With regard to approaches for modeling, such technologies like remote sensing, GIS, and environmental isotopes have also been applied to the establishment of regional groundwater flow model in addition to extensive use of MODFLOW, which are favorable for the settlement of some problems (Brodie, 1998; Ismael and Mohamed, 2007; Gogu et al., 2001).

studies in combination with this method have been drafted worldwide, and great achievements have also been obtained (Sophocleous et al., 1999; Sanford et al., 2004; Gedeon et al., 2007; Mayer et al., 2007; Furlong et al., 2011). Early in 1970s, relevant institutes in Australia carried out a battery of studies on large artesian basin in an attempt to forecast the trend of drop of hydraulic head and spring discharge of artesian basin in Australia through developing groundwater flow models for local and whole basin (Welsh and Doherty, 2006). Welsh established a steady flow (Welsh, 2000a) and a transient flow model by MODFLOW2000 (Welsh, 2000b) for the artesian basin with a simulation area of 150×10^4 km^2, and carried out calibration and verification of such model based on the monitoring data from 1965 to 1999. The size of the partition grid was 5 km×5 km with the number of active cells up to 6000. It can be deemed as the biggest groundwater flow modeling in the world at that time. The United States Geological Survey also carried out projects for regional water-bearing strata system in 1978 to facilitate simulation, analysis and management of the regional groundwater system (Sun and Johnson, 1994). In

Many predecessors have carried out a mass of hydrogeological work in the North China Plain since 1970s (Han, 2006; Ma et al., 2012). Besides extensive study of groundwater flow model (Zhang, 2007; Wang et al., 2007; Lin et al., 2007; Liu et al., 2008), plenty of approaches and propositions on sustainable development and utilization of water resources and environmental protection in this area have been put forward since the beginning of this century (Foster et al., 2004; Foster and Garduno, 2004; Kendy et al., 2007; Xu et al., 2008). Meanwhile, Chinese government has also implemented the South-North Water Transfer Project, which would be an important measure for alleviation of short supply of water resources in the North China Plain (Zhang, 2003). This project would also improve the regional ecological environment, and support the sustainable development of national economy in this area. Furthermore, with implementation of the South-North Water Transfer Project, great changes will take place to the water resources supply in the North China Plain. It will create favorable conditions for recovery of groundwater subjected to long-term uncontrolled pumping. Therefore, this study aims to develop a regional numerical groundwater flow model with certain precision for the North China Plain by groundwater modeling software GMS based on the existing data, so as to apply it to assess the safe yield of groundwater resources. Based on the supply and demand analysis of water resources, the established model would finally be used to evaluate the proposal for groundwater pumping and predict the recovery of groundwater level following implementation of the South-North Water Transfer Project. Such approaches will provide a scientific basis for sustainable utilization of groundwater in the North China Plain.

2 Hydrogeological Background

2.1 Hydrogeological structure

The North China Plain is a giant groundwater basin, of which groundwater is mainly deposited in the loose strata of the Quaternary System as formed by proluvial deposits, lacustrine deposits and marine deposits (Figure 2). It is in gradual transition from single unconfined aquifer as formed by gravels and pebbles at the upper and middle parts of piedmont alluvial-pluvial fan in the northwest to multiple aquifers as formed by sand, silt and clay at alluvial-lacustrine plain and coastal plain in the middle-east. Grain size gradually becomes fine from piedmont sand layer to that of offshore; whereas clay layer becomes thicker gradually. Meanwhile, sand layer is thinned out, and grain size becomes fine at the fan as well as land lots far away from the riverway. On the contrary, clay is well developed there.

Spatial distribution and circulation of groundwater in the study area have an obvious discrepancy due to complexity of spatial distribution of water-bearing media. Conventionally, water-bearing Quaternary strata of the North China Plain are divided into four aquifers according to the lithological distribution and hydraulic features of deposits, as well as present situation of development and utilization of groundwater: Burial depth of 1st, 2nd, 3rd and 4th aquifers is up to 10–60 m, 120–270 m, 250–350 m and 550–650 m respectively. The 1st aquifer is relatively thin and there is a close hydraulic connection between 1st and 2nd aquifers, and also there are many mixing pumping wells penetrating the two aquifers, thus, these two aquifers are integrated into one by the model in this study. 30 longitudinal and transverse hydrogeological profiles of the North China Plain were plotted based on the information on 2000 boreholes during the study, from which ground elevations of three aquifers were derived.

Aquifer parameters were determined based on the hydrogeological conditions of simulation area and work achievements of predecessors. Hydraulic conductivity and specific yield of unconfined aquifer are in a trend of reduction from piedmont alluvial-pluvial plain to both sides of the river valley. Variation range of hydraulic

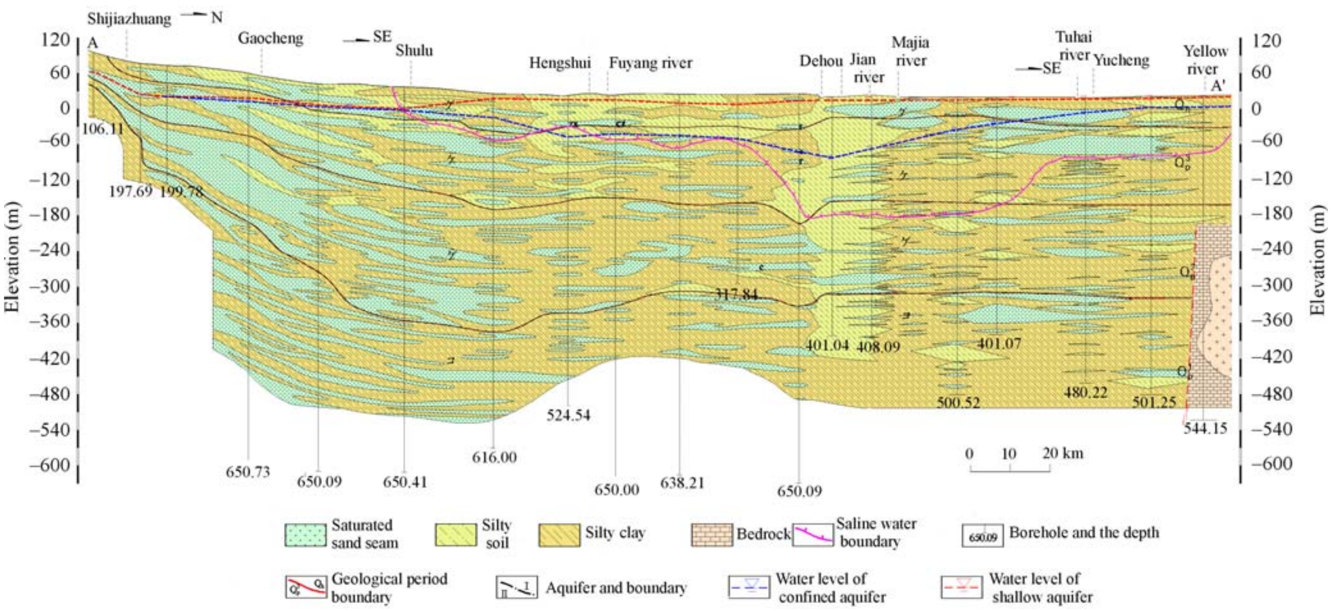

Fig. 2. Hydrogelogical cross section (from Shijiazhuang to Yucheng) of the North China Plain (I, the 1st aquifer; II, the 2nd aquifer; III, the 3rd aquifer; IV, the 4th aquifer).

conductivity and specific yield is 3 m/d–300 m/d and 0.03–0.23 respectively. Distribution range of hydraulic conductivity of confined aquifer is 1–50 m/d approximately with the order of magnitude of specific storage up to 10^{-4}–10^{-6}.

2.2 Groundwater recharge and discharge

Groundwater recharge in the study area is mainly supplemented by precipitation, lateral inflow, irrigation and river leakage. Precipitation serves as one of the major supplements for the groundwater in the area of study. The study aims to proceed with division of precipitation with Thiessen Polygon Method prior to calculation of infiltration volume of precipitation of each subarea with the method of precipitation infiltration coefficient. The volume of lateral inflow was obtained with profile method; whereas irrigation leakage was obtained with method of irrigation leakage coefficient. River leakage is mainly from lateral infiltration of Yellow River as derived based on the achievement of previous tasks with the profile method. As groundwater level in most areas in Hebei Plain is relatively deep with river water being intercepted by reservoirs in mountainous areas, groundwater-surface water exchange capacity is so limited.

Groundwater discharge is mainly by means of groundwater withdrawal and evapotranspiration. Groundwater withdrawal has become a major way for groundwater discharge in the area of study, supplying various needs of agricultural, municipal, and industrial use, as well as ecological use. Groundwater pumped from shallow aquifers is mainly concentrated in the piedmont belt; whereas groundwater pumped from deep aquifers is mainly concentrated in the central plain area of Hebei Province. The groundwater withdrawal in the North China Plain in 2002 and 2003 was 211.16×10^8 m^3 and 199.22×10^8 m^3 respectively. During the same period, the shallow groundwater withdrawal was 180.79×10^8 m^3 and 166.39×10^8 m^3 respectively; whereas the deep groundwater withdrawal was 30.37×10^8 m^3 and 32.83×10^8 m^3 respectively. Evapotranspiration intensity of groundwater in the area of study is varied, which has something to do with such factors as groundwater table, lithology of aeration zone, ground vegetations and climate, etc. According to previous research achievements, extinction depth in this area is 4 m. Monthly amount of evapotranspiration as submitted by meteorological stations at the county level is converted into evapotranspiration rate by Aviriyanover's Empirical Formula.

2.3 Boundary conditions

The natural boundary between mountains and plain in the west and north of the study area serves as the specified flux boundary for the 1st layer of the model (single phreatic aquifer). The 1st layer of the model accepts the lateral supplement via this boundary. Yellow River, which has a hydraulic connection with the 1st layer of the model, serves as the specified flux boundary in the south and southeast of the study area. The eastern part takes the coastline of Bohai Sea as the boundary, which is defined as the specified head boundary for the 1st layer of the model. The boundaries at 2nd layer and 3th layer are all defined as no-flow boundary (Figure 1).

Free water surface of unconfined aquifer serves as the upper boundary of the system, through which, vertical water exchange between phreatic water and environment outside groundwater system is realized, such as acceptance of water recharge from precipitation, irrigation leakage, and water discharge by evapotranspiration. Water exchange between each aquifer is realized through vertical leakage. Rock stratum below the 3rd aquifer is mainly composed of clastic rock of the Tertiary System, which is defined as no-flow boundary.

3 Methods

3.1 Mathematical model

Differential equation and finite solution for groundwater flow in the North China Plain can be obtained with the help of the hydrogeological conceptual model (Bear, 1979).

$$S\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)+\varepsilon \qquad x,y,z\in\Omega, t\geq 0$$

In the formula: Ω refers to flow domain; h refers to groundwater level (m); K_x, K_y and K_z represent hydraulic conductivity (m/d) of water-bearing media in the *x, y* and *z* directions; *ε* refers to sources and sinks (1/d); S refers to specific storage of aquifer below free water surface (1/m).

3.2 Establishment and calibration of groundwater flow model

The modeling aims to seek finite solutions to movement of groundwater by using groundwater modeling software---GMS (Groundwater Modeling System). This software is an advanced software in simulation of groundwater environment as developed by Environmental Modeling Research Laboratory at Brigham Young University (Zhu, 2003). Relevant packages in the GMS for processing of various boundary conditions, supplementary items and parameters such as WEL, RCH and EVT have been used during the study in addition to MODFLOW-groundwater flow simulation module (McDonald and Harbaugh, 1988).

The simulation area was subdivided into 164 rows and

148 columns with each layer being provided with 4 km× 4 km grids. The number of active cells (effective grids) of the 1st layer is 8694 while the 2nd layer and 3rd are both 7763.

It was determined based on the data collection and groundwater observation that the simulation would be carried out during the period from January 2002 to December 2003. Each calendar month was deemed as a stress period, during which, intensity of all the external sources and sinks would remain unchanged. The flow field by December 2001 and that by December 2003 were selected as the initial flow field and fitting flow field of the model respectively.

After introducing the hydrogeological conceptual model into GMS, the hydrogeological parameters and other hydrogeological conditions were further adjusted with predictor corrector method. Finally the model was verified through fitting of observed and simulated groundwater flow fields and comparison between observed and simulated hydrographs at typical observation wells. Fitting of the final flow field of 1st and 2nd aquifers is as shown in Figure 3. 64 observation wells were selected according to distribution of groundwater observation wells within the simulation area for comparison of the groundwater hydrographs. As indicated by statistic results (Table 1), mean absolute error is 1.69 m with that of 22 observation wells below 1m. Mean absolute error for 19 observation wells is up between 1m and 2 m; whereas that of 23 observation wells as sampled is over 2 m. Comparison of the observed and the simulated hydrographs at 6 typical

Table 1 Statistic results of error analysis of simulated water level

Mean Absolute Error(m)	<1	1–2	>2
Number of observation wells	22	19	23
Percentage (%)	34.38	29.69	35.93
Number of shallow seated observation wells	16	10	10
Number of deep seated observation wells	6	9	13

observation wells is as shown in Figure 4. Viewing from fitting of flow fields and comparison of groundwater hydrographs, simulation results have reflected the practical groundwater flow field and features of groundwater regime.

4 Evaluation and Estimation of Groundwater Resources

4.1 Groundwater recharge

Analysis of groundwater budget during the simulation period (Table 2) was carried out on the basis of groundwater modeling. In 2002, the total yearly amount of groundwater recharge in the North China Plain was up to 177.65×10^8 m^3 (except for interlayer leakage and lateral water exchange), and the total yearly amount of groundwater discharge was 281.91×10^8 m^3. Therefore, the storage variation was -104.26×10^8 m^3, which indicated that the groundwater in the study area was overexploited. The year 2003 was a wet year with total yearly groundwater recharge (except for interlayer leakage and lateral water exchange) and discharge in the North China

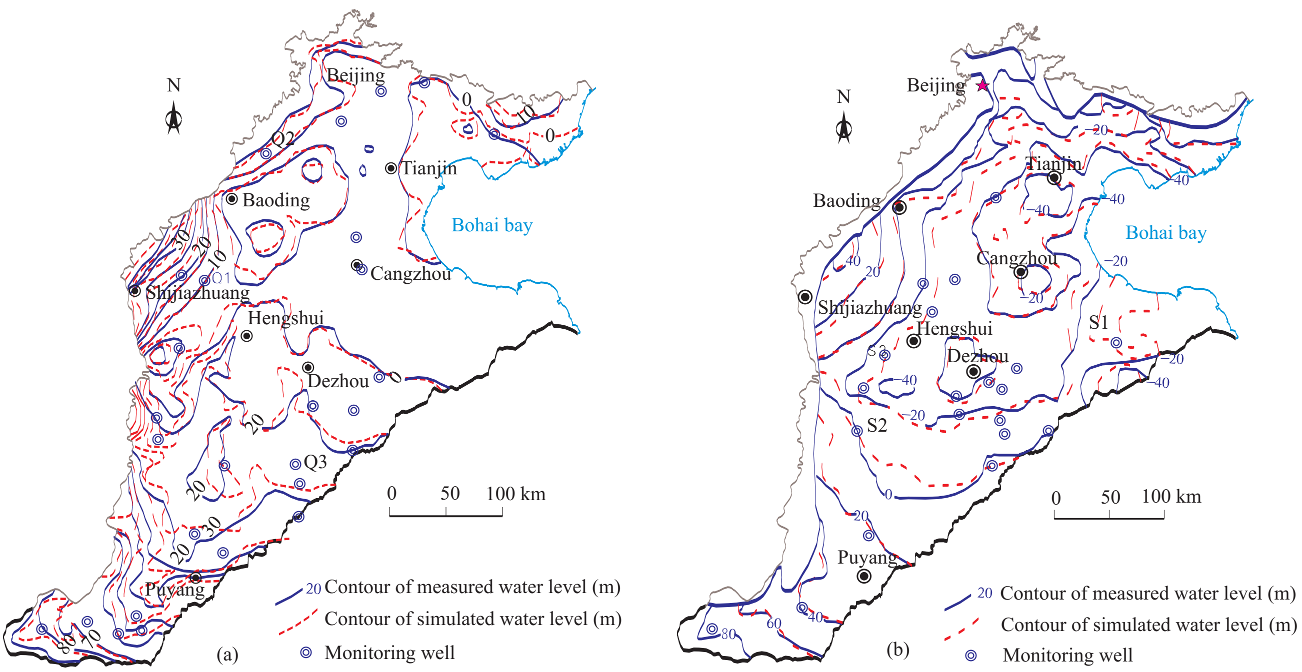

Fig. 3. Fitting of the observed and the simulated groundwater flow fields of the North China Plain (a, unconfined aquifer; b,confined aquifer).

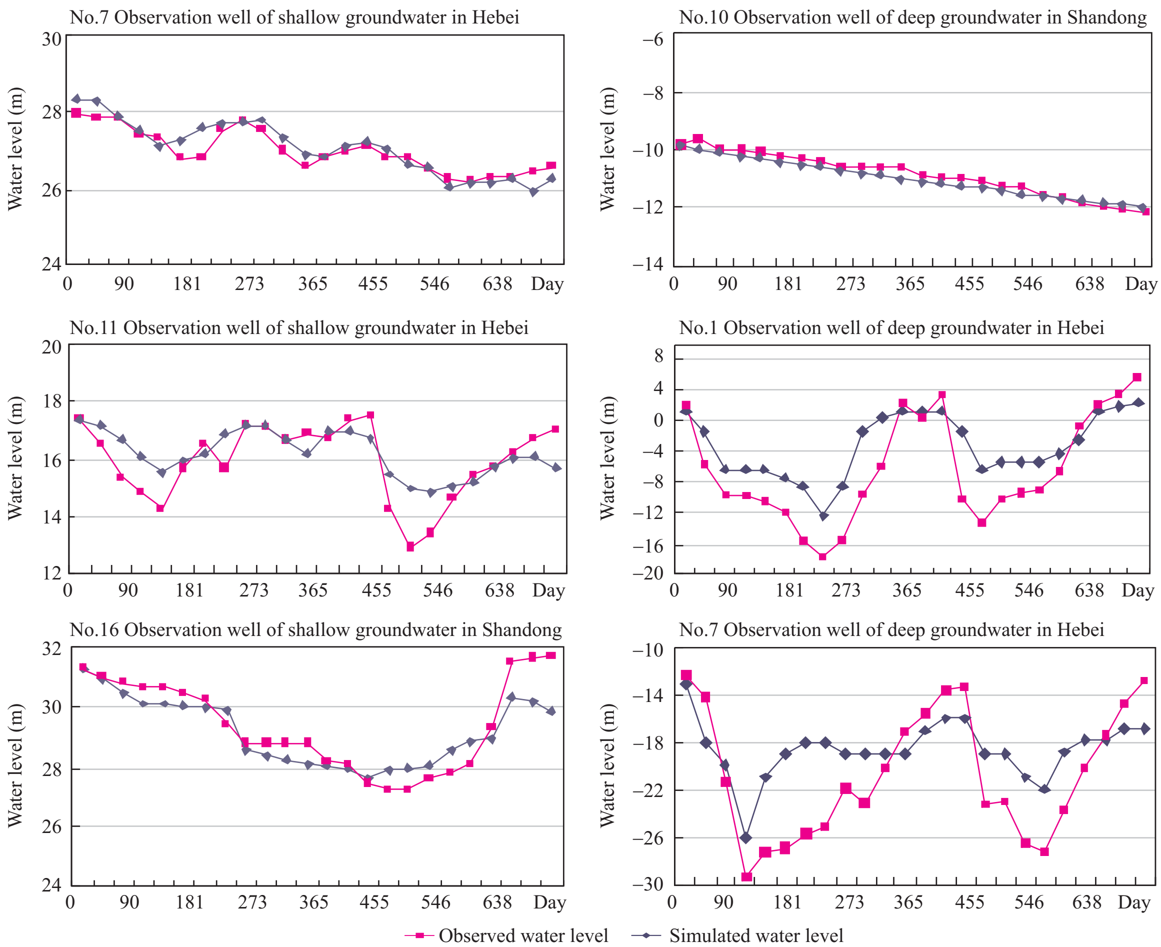

Fig.4. Observed vs. simulated hydrographs at six specific observation wells

Table 2 Groundwater budgets in 2002 and 2003 ($10^8 m^3$)

	Budget Items	2002		2003	
		Shallow/deep	Total	Shallow/deep	Total
Recharge Items	Rainfall infiltration	118.14/	118.14	225.07/	225.07
	River leakage	5.89/	5.89	5.89/	5.89
	Canal leakage	12.28/	12.28	10.12/	10.12
	Canal irrigation infiltration	9.35/	9.35	7.45/	7.45
	Well irrigation infiltration	17.82/	17.82	16.23/	16.23
	Lateral infiltration	14.17/	14.17	14.17/	14.17
	Interlayer leakage	/19.80		/24.32	
	Subtotal	177.65/19.80	177.65	278.93/24.31	278.93
Discharge items	Pumping volume	180.79/30.37	211.16	166.39/32.83	199.22
	Evapotranspiration	70.75/	70.75	48.89/	48.89
	Interlayer leakage	19.80		24.31/	
	Subtotal	271.34/30.37	281.91	239.59/32.83	248.11
Storage variation		−93.69/−10.57	−100.26	39.34/−8.52	30.82

Plain up to 278.93×10^8 m^3, 248.11×10^8 m^3 respectively. So the storage variation in 2003 was 30.82×10^8 m^3, which showed that the groundwater in the North China Plain was generally in positive balance. From Table 2, it can be seen that precipitation infiltration serves as the main source of recharge to groundwater in the area of study, which is followed by irrigation infiltration (including leakage from surface water, groundwater irrigation and canal). Groundwater withdrawal serves as the main discharge followed by evapotranspiration from phreatic water.

According to evaluation in combination with information on precipitation and rivers for previous years on the basis of water budget analysis, the average annual groundwater recharge in the North China Plain from 1991 to 2003 was up to 256.68×10^8 m^3/yr with average recharge modulus up to 18.47×10^4 m^3/(km^2·yr). The rainfall infiltration was 179.70×10^8 m^3/yr, accounting for 70% of the total. As calculated with method of water budget, average annual groundwater recharge during the same period was up to 252.38×10^8 m^3/yr (Zhang, 2009), which has also verified the accuracy of this model.

4.2 Safe yield of groundwater resources

With regard to shallow groundwater under the existing (over-exploitation area) and planned (non-over-exploitation area) exploitation conditions, the safe yield of shallow groundwater, which is defined as the maximum volume (m^3) of groundwater that can be abstracted in shallow aquifer in the North China Plain per annum without causing negative impacts on the environment, was calculated through operation of this model for 10 years based on the analysis of groundwater flow field, groundwater recharge, storage variation and water exchange between each layer.

To a great extent, deep groundwater resources (groundwater resources at the 2nd and 3rd aquifers) belong to consumable resources. Under existing pumping conditions, the groundwater pumped from deep aquifers is mainly supplemented by vertical leakage from upper shallow aquifer, lateral inflow from single aquifer area, elastic yield as incurred by head drop and compression-releasing water from aquitards. From the point of view of sustainable development, the groundwater recharge for deep aquifers should serve as the safe yield of deep groundwater. However, the volume of groundwater pumped from deep aquifers in many areas is usually greater than the volume that can be recharged. In fact, it is difficult to evaluate the safe yield of deep groundwater theoretically. Approach adopted for evaluating the safe yield of deep groundwater in this study is stated as follows: (1) Prohibit use of elastic yield from deep aquifers in the areas where deep groundwater is developed and utilized excessively; the safe yield of deep groundwater for such places equals to the recharge from interlayer leakage and lateral inflow; (2) it is necessary to consider use of safe elastic yield from deep aquifers under existing exploitation conditions in the area where the degree of development and utilization of deep groundwater is low. The safe yield of deep aquifers in each area (prefecture cities) shall be obtained through comprehensive analysis of vertical leakage, lateral inflow, and storage variation of deep aquifers as estimated through operation of the model for 10 years in comprehensive consideration of aforementioned factors.

Total safe yield of groundwater resources in the North China Plain as obtained through aforementioned calculations is 213.49×10^8 m^3/yr, of which the safe yield of shallow groundwater accounts for 191.65×10^8 m^3/yr with safe yield modulus, the safe yield of groundwater per unit area, up to 13.79×10^4 $m^3/(km^2\cdot yr)$, while the safe yield of deep groundwater accounts for 22.64×10^8 m^3/yr with safe yield modulus up to 1.93×10^4 $m^3/(km^2\cdot yr)$. The results of the evaluation is similar to that as obtained with water budget method[5]. Safe yield modulus of each prefecture city in the North China Plain is as shown in Figure 5.

5 Forecast on Changing Trend of Groundwater regime after Commencement of Water Supply by South-North Water Transfer Project

The proposal of groundwater withdrawal in the North China Plain for the period from 2010 to 2020 (Table 3) was planned in consideration of specific situation of water resources and economic development status in each province and city, as well as relevant water supply planning of South-North Water Transfer Project. In this prediction work, the practical flow field by December 2003 was used as the initial flow field of groundwater before water supply from South-North Water Transfer Project; whereas the recharge and discharge items adopted the average annual values during the period from 1991 to 2003. Eventually changing trend of groundwater regime during 2011-2020 (10 years after implementation of South-North Water Transfer Project) was forecasted with the established groundwater model

As indicated by simulation results, recovery of groundwater at piedmont shallow aquifer is obvious in the key regulated area as described in the proposal for water supply of South-North Water Transfer Project (Figure 6). For instance, 1.42×10^8 m^3 groundwater withdrawal would be reduced annually in Shijiazhuang. Existing urban depression cone center-Shijiazhuang depression cone would be thoroughly recovered with water level up to 21 m; water level at Gaoliqing depression cone will rise by 10 m approximately. However, the situations at depression

Table 3 Safe yield and planned pumping volume of groundwater under the condition of South-to-North Water Transfer Project in the North China Plain ($10^8 m^3$/yr)

Provinces/Cities	Safe yield			Planned pumping volume in 2010			Planned pumping volume in 2020		
	Shallow	Deep	Total	Shallow	Deep	Total	Shallow	Deep	Total
Beijing	20.50	0.97	21.47	20.49		20.49	20.49		20.49
Tianjin	2.75	2.20	4.95	1.20	2.33	3.53	1.20	2.33	3.53
Hebei Province	95.77	14.13	109.90	93.04	19.03	112.07	94.56	19.06	113.62
Henan Province	33.98	3.06	37.04	27.97		27.97	39.06		39.06
Shandong Province	37.74	2.29	40.03	37.28	2.31	39.59	37.28	2.31	39.59
Total	190.84	22.64	213.48	179.98	23.67	203.65	192.59	23.70	216.29

cones in Baoding, Ningbolong and Fengrun, where the groundwater withdrawal is mainly used for agriculture, will not be improved but instead be in a trend of intensification. Water level at Ningbolong depression cone center would drop to −25~−27 m; whereas that at Baoding depression cone would drop to −15~−23 m. Generally speaking, groundwater in Beijing would be recovered to some extent except for slight drop of water level on the outskirts. Changing trend of shallow groundwater regime at typical areas is as shown in Figure 6. Depression cone centers of deep groundwater would still be concentrated in Tianjin, Cangzhou, Dezhou and Hengshui despite significant reductions in cone range and obvious rise of water level after implementation of South-North Water Transfer Project for 10 years, (Figure 7). Rise of water level in Dezhou is the most significant, which is by 8~15m; whereas average annual rise rate in Bingcheng District is up to 0.6–1 m/yr. However, Ninghe country, Dongli District, Beichen District of Tianjin would all witness a continuous drop of water level due to increase in groundwater pumping. Average annual drop rate is up to 0.8–1.7 m/yr.

Fig. 5. Division of safe yield modulus of each prefecture city.

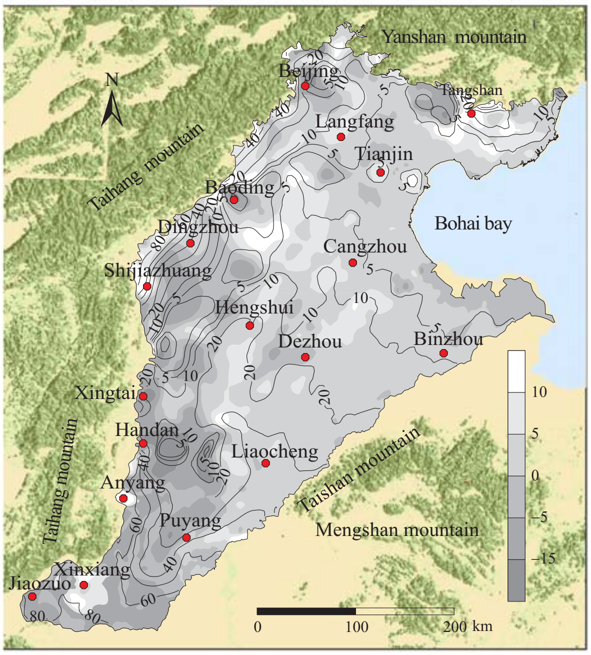

Fig. 6. Simulated water level contour of unconfined aquifer for 2020 and water level change from 2011 to 2020 in the North China Plain.

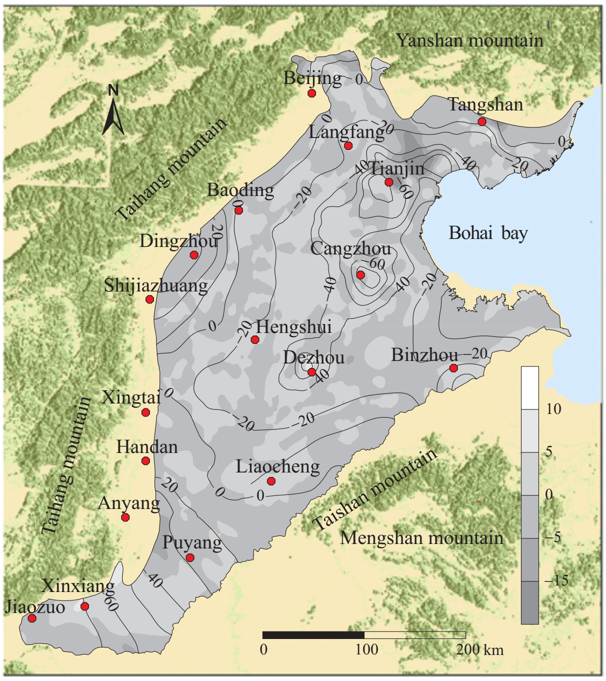

Fig. 7. Simulated water level contour of confined aquifer for 2020 and water level change from 2011 to 2020 in the North China Plain.

6 Discussions

Due to large dimension of the study area and lack of data for the model, there are some limitations existing in the established model.

First of all, the established model is considered as a regional groundwater flow model and the research on it belongs to a large-scale study. This regional model with big-size grids cannot represent the hydrogeological conditions of the study area as precisely as the model with small-size grids does. Therefore, there is a problem of accuracy in this model. Moreover, if putting this model into practical work, it would meet difficulties in reflecting or dealing with some local water resources and environment problems in the study area.

In addition, because of the lack of the collected data and the limited research conducted on the study area, the simulation period is only one year, which would result in some errors when the model is used to predict the perennial groundwater regime of the study area.

To solve the problem of accuracy existing in the model, some measures could be taken in the future for model improvement.

One solution is to use local grid refinement techniques to achieve refined grids in some local areas like well fields which require to be accurately modeled by smaller grid spacing. The local grid refinement techniques have been widely studied in the field of numerical model of groundwater flow (Szekely, 1998; Mehl and Hill, 2002; Mehl and Hill, 2004; Dickinson et al, 2007). One of the most commonly employed local grid refinement methods nowadays is using the Local Grid Refinement (LGR) module in MODFLOW2005 (Mehl and Hill, 2007). By taking this method, the regional model and the local model can be coupled through the two-way iteration of the shared boundary. Thereupon the groundwater changing trend in local places will be reflected in a more accurate and effective way.

Besides, if the entire domain is discretized into fine grids, parallel computing methods could be used to overcome the limitation of traditional single central processing unit computers and meet the modeling requirement for intensive computational ability and large amounts of memory space. At present, many countries have widely adopted this effective method to solve problems of complicated aquifer systems (Gwo et al, 2001; Mills et al, 2007; McLaughlin, 2008; Zhang et al, 2008; Cheng et al, 2009;). When it comes to problem of large-scale numerical simulation of groundwater flow which requires high degree of accuracy, the effective parallel computing methods could help improve the computational performance of MODFLOW and reduce the execution time of MODFLOW (Dong and Li, 2009). Thereby, the research ability on the numerical simulation of groundwater flow could also be greatly improved.

With regard to prediction errors existing in the model, the errors could be reduced by prolonging the simulation period of groundwater model, or developing a perennial steady-state flow model.

Although there are some disadvantages existing in the model, it still serves as an effective tool for the study of reasonable development and utilization of groundwater in practical work. Other than predicting the groundwater changing trend after the water supply by South-North Water Transfer Project, the groundwater flow model is also available for the following tasks:

(1) Great changes will take place to the distribution of water resources after commencement of water supply from South-North Water Transfer Project. Reasonable development and utilization of groundwater is of vital significance to the recovery of groundwater storage and geological environment as well as assurance of the safe water supply in this area. Thus this model can be used to forecast recovery of groundwater under various constrictions, and provides scientific basis for draft of scientific, reasonable and feasible proposal for control and exploitation of groundwater (Cui et al., 2009).

(2) It is also applicable to proceed with analysis of overexploited situation and exploitation potential of groundwater based on the evaluation of the safe yield of groundwater resources according to present situation of groundwater so as to put forward a reasonable proposal for exploitation of groundwater, and make use of the model to verify reasonability and feasibility of such a proposal.

(3) Under the conditions of various groundwater pumping proposals, groundwater flow field and dynamic trend can be predicted with the model, and accordingly the environmental impact due to groundwater exploitation can also be evaluated.

7 Conclusions

To ensure scientific and reasonable evaluation of groundwater resources in the North China Plain, groundwater model software-GMS was used in this study to establish a 3D groundwater flow model for the North China Plain. In order to make sure that the established model can reflect hydrogeological conditions and features of groundwater flow system in the area of study to the maximum, the predictor corrector method was used in the study for model calibration, and model verification was based on the fitting of observed and simulated flow fields in 2003 and comparison between the observed and the simulated hydrographs at 64 typical observation wells. As indicated by error analysis, this model has reflected features of groundwater flow in the North China Plain. According to evaluation based on water budget analysis, average amount of groundwater recharge in the North China Plain during the period from 1991 to 2003 was 256.68×10^8 m^3/yr with average recharge modulus up to 18.47×10^4 $m^3/(km^2\cdot yr)$. According to comprehensive evaluation based on operation of established groundwater flow model for 10 years, the safe yield of groundwater resources in the North China Plain was 213.49×10^8 m^3/yr with that of shallow and deep groundwater up to 191.65×10^8 m^3/yr and 22.64×10^8 m^3/yr respectively.

Finally, changing trends of groundwater in the North China Plain for the coming 10 years (2011–2020) were forecasted through integration of this model with proposal for water supply of the South-North Water Transfer Project. As indicated by relevant results, water level at shallow groundwater depression cone center within the key controlled area as described in the water supply proposal would witness a rise to some extent. Annual rise rate of water level in Shijiazhuang is up to 2.1 m/yr. Coverage of the influence of deep groundwater depression cone would witness a significant reduction. Annual rise rate of water level in Dezhou is up to 0.8–1.5 m/yr. Thus, it can be seen that South-North Water Transfer Project will play an important role in promoting the rise of groundwater in the North China Plain.

Acknowledgments

This work was supported by a grant from the National Basic Research Program of China (973 Program) (No. 2010CB428804). The authors are grateful to the Institute of Hydrogeology and Environmental Geology, Beijing Institute of Geological Survey, Tianjin Institute of Geological Survey, Heibei 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.

Manuscript received Sept. 21, 2011
accepted Aug. 20, 2012
edited by Fei Hongcai

References

Belcher, W.R., ed., 2004. Death Valley regional groundwater flow system, Nevada and California–Hydrogeologic framework and transient ground-water flow model. In: *USGS Scientific Investigations Report 2004–5205*, 408.

Brodie, R.S., 1998. Integrating GIS and RDBMS technologies during construction of a regional groundwater model. *Environmental Modeling & Software*, 14: 119–128.

Bear, J., 1979. *Hydraulics of Groundwater*. McGraw-Hill Inc.: 116–152.

Cui Yali, Wang Yabin Shao Jingli, Chi Yaping and Lin Li, 2009. Research on groundwater eegulation and recovery in North China Plain after the implementation of South-to-North Water Transfer. *Resources Science*, 3: 382–387 (in Chinese with English abstract).

Cheng Tangpei, 2011. *Research on Efficient Parallel Computing for Ground Water Flow Simulation.* China University of Geosciences in Beijing (Ph. D thesis): 2-3 (in Chinese with English abstract).

Cheng, T.P., Ji, X.H., and Wang, Q., 2009. An efficient parallel method for large-scale groundwater flow equation based on PETSc. In: *Proceedings*, *IEEE Youth Conference on Information, Computing and Telecommunication*, 190–193.

D'Agnese, F.A., O'Brien, G.M., Faunt, C.C., Belcher, W.R., and Juan, C.S., 2002. A three-dimensional numerical model of predevelopment conditions in the Death Valley Regional Ground-Water Flow System, Nevada and California. In: *USGS Water-Resources Investigations Report 02–4102*, 114.

DeMeo, G.A., Laczniak, R.J., Boyd, R.A., Smith, J.L., and Nylund, W.E., 2003. Estimated ground-water discharge by evapotranspiration from Death Valley, California, 1997–2001. In: *USGS Water-Resources Investigations Report 03–4254*, 27.

Dickinson, J.E., James, S.C., Mehl, S., Hill, M.C., Leake, S.A., Zyvoloski, G.A., Faunt, C.C., Eddebbarh, A., 2007. A new ghost-node method for linking different models and initial nvestigations of heterogeneity and nonmaching grids. *Advances in Water Resources*, 30: 1722–1736.

Dong, Y.H., and Li, G.M., 2009. A parallel PCG solver for MODFLOW. *Ground Water*, 47: 845–850.

Furlong, B.V., Riley, M.S., Herbert, A.W., Ingram, J.A., Mackay, R., and Tellam, J.H., 2011. Using regional groundwater flow models for prediction of regional wellwater quality distributions. *Journal of Hydrology*, 398: 1–16.

Foster, S., Garduno, H., Evans, R., Olson, D., Tian Yuan, Zhang Weizhen and Han Zaisheng, 2004. Quaternary aquifer of the the North China Plain – assessing and achieving groundwater resource sustainability. *Hydrogeology Journal*, 12: 81–93.

Foster, S. and Garduno, H., 2004. China: towards sustainable groundwater resource use for irrigated agriculture on the North China Plain. In: *GW.MATE Case Profile Collection number 8.* The World Bank, Washington D.C., USA, 1–16.

Gogu, R.G., Carabin, G., Hallet, V., Peters, V., and Dassargues, A., 2001. GIS-based hydrogeological databases and groundwater modeling. *Hydrogeology Journal*, 9: 555–569.

Gwo, J. P., D'Azevedo, E. F., Frenzel, H., Mayes, M., Yeh, G.T., Jardin, P.M., Salvage, K.M., and Hoffman, F.M., 2001. HBGC123D: A high-performance computer model of coupled hydrogeological and biogeochemical processes. *Computers and Geosciences*, 27: 1231–1242.

Gedeon, M., Wemaere, I., and Marivoet, J., 2007. Regional groundwater model of north-east Belgium. *Journal of Hydrology*, 335: 133–139.

Han Zaisheng, 2006. Alluvial aquifers in the North China Plain. In: *International symposium – Aquifer Systems Management: Darcy's Legacy in a World of Impending Water Shortage*: 117–126.

Ismael, A.A., and Mohamed, A., 2007. *Applications of Remote Sensing, GIS, and Groundwater Flow Modeling in Evaluating Groundwater Resources: Two Case Studies; East Nile Delta, Egypt and Gold Valley, California, USA*. The University of Texas at El Paso (Ph. D thesis): 1–402.

Kendy, E., Wang Jinxia, Molden, D.J., Zheng Chunmiao, Liu Changming and Steenhuis, T.S., 2007. Can urbanization solve inter-sector water conflicts? Insight from a case study in Hebei Province, the North China Plain. *Water Policy 9 Supplement 1*: 75–93.

Liu Changming, Yu Jingjie and Kendy, E., 2001. Groundwater exploitation and its impact on the environment in the North China Plain. *Water International*, 26(2): 265–272.

Lin Li, Yang Feng, Cui Yali, and Shao Jingli, 2007. FEFLOW modeling techniques applied in groundwater system of large-scale areas. *Beijing Water*, 1: 43–46 (in Chinese with English abstract).

Liu Jie, Zheng Chunmiao, Zheng Li and Lei Yuping, 2008.

Ground water sustainability: methodology and application to the North China Plain. *Ground Water*, 6(46): 897–909.

Ma Fengshan, Wei Aihua, Han Zhantao, Zhao Haijun and Guo Jie, 2011. The characteristics and causes of land subsidence in Tanggu based on the GPS survey system and numerical simulation. *Acta Geologica Sinica* (English edition), 85(6): 1495–1507.

Ma Rong, Shi Jiansheng and Liu Jichao, 2012. Dealing with the spatial synthetic heterogeneity of aquifers in the North China Plain: a case study of Luancheng country in Hebei province. *Acta Geologica Sinica* (English edition), 86(1): 226–245.

McDonald, M.G., and Harbaugh, A.W., 1988. A modular three-dimensional finite-difference ground-water flow model. In: *Techniques of Water-Resources Investigations of USGS. Book 6, Chapter A1*: 586.

Moreo, M.T., Halford, K.J., La Camera, R.J., and Laczniak, R.J., 2003. Estimated ground-water withdrawals from the Death Valley Regional Flow System, Nevada and California, 1913–98. In: *USGS Water-Resources Investigations Report 03–4245*, 28.

Mayer, A., May, W., Lukkarila, C., and Diehl, J., 2007. Estimation of fault-zone conductance by calibration of a regional groundwater flow model: Desert Hot Springs, California. *Hydrogeology Journal*, 15: 1093–1106.

Mehl, S.W., and Hill, M.C., 2002. Development and evaluation of a local grid refinement method for block-centered finite-difference groundwater models using shared nodes. *Advances in Water Resources*, 25: 497–511.

Mehl, S.W., and Hill, M.C., 2004. Three-dimensional local grid refinement for block-centered finite-difference groundwater models using iteratively coupled shared nodes: a new method of interpolation and analysis of errors. *Advances in Water Resources*, 27: 899–912.

Mehl, S.W., Hill, M.C., 2007. MODFLOW-2005, the U.S. Geological Survey modular ground-water model—Documentation of shared node local grid refinement (LGR) and the boundary flow and head (BFH) package. In: *U.S. Geological Survey Techniques and Methods*, 6-A21: 13.

McLaughlin, J.D., 2008. *Parallel Processing of Reactive Transport Models Using OpenMP*. Brigham Young University (Master's thesis): 1–82.

Mills, R.T., Lu, C., Lichtner, P.C., Hammond, G.E., 2007. Simulating subsurface flow and transport on ultrascale computers using PFLOTRAN. *Journal of Physics: Conference Series,* 78: 1-7.

Sophocleousa, M.A., Koelliker, J.K., Govindaragu, R.S., Ramireddygarie, S.R., and Perkins, S.P., 1999. Integrated numerical modeling for basin-wide water management: the case of the Rattlesnake Creek basin in south-central Kansas. *Journal of Hydrology*, 214: 179–196.

Sanford, W.E., Plummer, L.N., McAda, D.P., Bexfield, L.M., and Anderholm, S.K., 2004. Hydrochemical tracers in the middle Rio Grande Basin, USA: 2. calibration of a groundwater - flow model. *Hydrogeology Journal*, 12: 389–407.

Sun, R.J., and Johnson, R.H., 1994. Regional aquifer system analysis program of the U.S. Geological Survey 1978–1992. In: *U.S. Geological Survey Circular1099*, 126.

Székely, F., 1998. Windowed spatial zooming in finite-difference ground water models. *Ground Water*, 36(5): 718–721.

Wang Shiqin, Song Xianfang, Wang Qinxue, Xiao Guoqiang, Liu Changming and Liu Jianrong, 2009. Shallow groundwater dynamics in North China Plain. *Journal of Geographical Sciences*, 19: 175–188.

Welsh, W.D., and Doherty, J., 2006. Great Artesian Basin groundwater modeling. In: *29th Hydrology and Water Resources Symposium – Water Capital*, Canberra, 18.

Welsh, W.D., 2000a. GABFLOW: A steady state groundwater flow model of the Great Artesian Basin. In: *Bureau of Rural Sciences, Canberra*, 75.

Welsh, W. D., 2000b. Great Artesian Basin transient groundwater model. In: *Bureau of Rural Sciences, Canberra*, 58.

Wang Shiqin, Shao Jingli, Song Xianfang, Zhang Yongbo, Zhou Xiaoyuan, and Huo Zhibin, 2007. The application of groundwater model, MODFLOW, and GIS technology in the dynamic evaluation of groundwater resource in the North China Plain. *Geographical Research*, 26(5): 975–983 (in Chinese with English abstract).

Xu Yeshuang, Shen Shuilong, Cai Zhengyin, and Zhou Guoyun, 2008. The state of land subsidence and prediction approaches due to groundwater withdrawal in China. *Natural Hazards*, 45: 123–135.

Xia Jun, 2002. A perspective on study of hydrological base of water security problem and its challenges in North China. *Progress in Geography*, 21(6): 517–526 (in Chinese with English abstract).

Zhang Zonghu, 2005. Groundwater in the vast North China Plain. *Chinese Journal of Nature*, 27(6): 311–315 (in Chinese with English abstract).

Zheng Chunmiao, Liu Jie, Cao Guoliang, Kendy, E., Wang Hao and Jia Yangwen, 2010. Can China cope with its water crisis? – perspectives from the North China Plain. *Ground Water*, 48 (3): 350–354.

Zhang Zhaoji, Fei Yuhong, Chen Zongyu, Zhao Zongzhuang, Xie Zhenhua, Wang Yabin, Miao Jinxiang, Yang Lizhi, Shao Jingli, Jin Menggui, Xu Guangming, Yang Xiqin, Zhang Fenger, Luo Guozhong, Liu Lijun, Gao Hongqiang, Chen Zhihong, Wangjiabin, Wu Jichen, Cui Yali, Wang Qiang, Wang Zhao, Chen Jinsheng, Jiang Xianqiao, Xin Guozhang, Liu Chunhua, Liu Zhongye, Wang Binguo, Chen Yong and Ding Wenping, 2009. *Investigation and assessment of sustainable utilization of groundwater resources in the North China Plain*. Beijing: Geological Publishing House: 41–78, 258–269 (in Chinese with English abstract).

Zhang Xiaoming, 2007. Study on groundwater modeling of Huabei Plain, Haihe watershed. *Haihe Water Resources*, 3: 52–54 (in Chinese with English abstract).

Zhang Weizhen, 2003. The function of rational exploitation and utilization of groundwater resources in South-To-North Water Transfers Project. *South-to-North Water Transfers and Water Science and Technology*, 1(4): 1–7 (in Chinese with English abstract).

Zhu Xiaobin, 2003. Groundwater modeling system (GMS) software. *Hydrogeology and Engineering Geology*, 5: 53–55 (in Chinese with English abstract).

Zhang, K.N., Wu, Y.S., and Bodvarsson, G.S., 2003. Parallel computing simulation of fluid flow in the unsaturated zone of Yucca Mountain, Nevada. *Journal of Contaminant Hydrology*, 62–63: 381–399.