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ORIGINAL ARTICLE

Application of MODFLOW and geographic information system to groundwater flow simulation in North China Plain, China

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Abstract MODFLOW is a groundwater modeling program. It can be compiled and remedied according to the practical applications. Because of its structure and fixed data format, MODFLOW can be integrated with Geographic Information Systems (GIS) technology for water resource management. The North China Plain (NCP), which is the politic, economic and cultural center of China, is facing with water resources shortage and water pollution. Groundwater is the main water resource for industrial, agricultural and domestic usage. It is necessary to evaluate the groundwater resources of the NCP as an entire aquifer system. With the development of computer and internet information technology it is also necessary to integrate the groundwater model with the GIS technology. Because the geological and hydrogeological data in the NCP was mainly in MAPGIS format, the powerful function of GIS of disposing of and analyzing spatial data and computer languages such as Visual C and Visual Basic were used to define the relationship between the original data and model data. After analyzing the geological and hydrogeological conditions of the NCP, the groundwater flow numerical simulation modeling was constructed with MODFLOW. On the basis of GIS, a dynamic evaluation system for groundwater resources under the internet circumstance was completed. During the process of constructing the groundwater model, a water budget was analyzed, which showed a negative budget in the NCP. The simulation period was from 1 January 2002 to 31 December 2003. During this period, the total recharge of the groundwater system was $49{,}374 \times 10^6$ m^3 and the total discharge was $56{,}530 \times 10^6$ m^3 the budget deficit was $-7{,}156 \times 10^6$ m^3. In this integrated system, the original data including graphs and attribution data could be stored in the database. When the process of evaluating and predicting groundwater flow was started, these data were transformed into files that the core program of MODFLOW could read. The calculated water level and drawdown could be displayed and reviewed online.

Keywords Groundwater model · MODFLOW · GIS · Integration · North China Plain · Water resources

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Introduction

Nowadays, the numerical modeling technology has become an important method on the groundwater research. And many visual numerical modeling software of groundwater based on different methods have been developed and used widely such as Finite Element subsurface FLOW system (FEFLOW) (Diersch 2005), Groundwater Modeling System (GMS) (Anon. 2000), Visual Modular three Dimensional Flow (Visual MODFLOW) (Anon. 2000), a 2D and 3D geostatistics, uncertainty analysis and visualization software package (UNCERT) (Wingle et al. 1999) and Proceessing

MODFLOW for Window (PMWIN, Chiang and Wen–Hsing 2005). Of them, MODFLW (McDonald and Harbaugh 1988) was used as calculation program broadly because of its simple methods, modular program structure and separate package to resolve special hydrogeologic problems. For example, the popular software of GMS, Visual MODFLOW and PMWIN were all developed based on MODFLOW program. Combing with GIS technology they provided good visualization interface for user and played a significant role in the groundwater evaluation and management of many countries. From now on, many 2-D or 3-D groundwater flow quantity and quality models have been constructed successfully to resolve many groundwater flow problems.

However, above visualization processors have some disadvantages to the user. First, they are commercially expensive and some user cannot afford it (Carrera–Hernandez and Gaskin 2006). Second, the user cannot be provided access to their source code and they have to prepare the input file to build a model according to the fixed format of the software and they cannot modify the calculating program. Because the source code of MODFLOW is open on the internet and its functions are powerful, many people began to develop their own model by integrating MODFLOW into their own geologic information system (GIS) instead using visualization software directly. Knab et al (1998) created the user interface of MODFLOW, MODPATH and MT3D based on the AutoCAD. Heinzer and Hansen (1999) developed the user interface to construct the groundwater flow model. In that system the model grid, input and output data can be saved as a separate raster dataset. Brodie (1999) developed the Lower Darling model, southeast Australia, combining a relational database management system (RDBMS) which was used to manage the borehole and GIS which was used to manage spatial information as the working environment. Tsou and Whittemore (2001) integrated the MODFLOW, the solute transpiration model MT3D and the ARCVIEW interface environment including the input data of various point, line and polygon data and the result display. Especially, it used the extension module of 3D Analyst to link the database. Also GIS was used to link two models such as a conceptual vadose zone model SWAT and MODFLOW for the total basin management (Sophocleous et al. 1999; Facchi et al. 2004). Carrera–Hernandez and Gaskin (2006) created a module in the Open Source Geographic Resources Analysis Support System (GRASS) GIS to integrate it with the finite difference groundwater flow model MODFLOW which are both open source software. As to these systems GIS was used as a tool to link with model. It requires the transfer of information between the GIS and the model. GIS and model can have no direct connection and information transfer is assumed by input–output routines added to the model (Srinivasan and Engel 1991; Tim and Jolly 1994; Flugel and Micht 1995; San and Kolm 1996).

In this paper, the groundwater MODFLOW was not only linked by GIS but also was integrated under the internet environment with GIS technology. This was done on the "863" planning of National Geology Grid of Chinese Geology Survey (Zhang et al. 2006). In this planning, the evaluation model could be shared with network technology and it could integrate the database of China which has collected large number of temporal and spatial data. In China, most geological and hydrogeological spatial data were stored in a Geologic Information System (MAPGIS) format developed by China Geoscience University (Wuhan). Therefore to transfer the information between the MAPGIS and the MODEL during input–output routines was important when building the model. It was necessary to understand the structure, principle of MODFLOW source code and physical significances of all kind of parameters. Then the relationship between input or output data format of the model and the MAPGIS data or non-spatial data information in China was founded. As a case of North China Plain (NCP), where water shortage and water pollution was very serious and groundwater was the major water supply to agricultural, industrial and domestic usage, though several regional model in NCP had been constructed (Wei et al. 2003; Jia et al. 2003; Zheng 2007), the model of entire of aquifer system of the NCP have never been done before. In this paper a 3-D transient groundwater flow model was constructed and integrated with Chinese GIS database under internet environment in order to evaluate and manage the water resource dynamically.

Integration process of groundwater model and GIS

Features of MODFLOW

MODFLOW is programmed under the FORTRAN 77 (American National Standards Institute 1978) language environment with the finite–difference method to describe the movement of groundwater flow. It was developed by McDonald and Harbaugh(1984) of US Geology Survy in 1984 and had been updated for three times including MODFLOW-88(McDonald and Harbaugh 1988), MODFLOW-96 (Harbaugh and McDonald 1996) and MODFLOW-2000 (Harbaugh et al. 2000). The newest version of MODFLOW-2000 could be compiled by FORTRAN language of Visual Studio program and general language of C could be used here. At the same time many new packages were added into the code which can simulate the hydrogeologic problems much better than ever. For example, Reservoir Package (RES1) (Fenske et al. 1996) can simulate leakage from reservoirs; Evapotranspiration with a segmented function (ETS1) (Banta 2000) package allows simulation of evapotranspiration with a user-defined relation between evapotranspiration rate and hydraulic head; Drain Return (DRT1) (Banta 2000) Package can be used to simulate the return flow of water discharged from a drain back into the ground-water system. These packages can be used separately by main program during calculating the model and each package is divided into different modules and each module executes different procedures to finish certain part of simulation such as defining model, allocating memory, reading data, formulating equations. The separate feature is benefit for users to modify program or add new package to the main program.

Generally, a simulation process involves input process, calculation core program and output process. The input data of the model include different files according to data pattern and each file records some parameters to construct a groundwater model. For example, Discretization (DIS) file is to define the structure of a model, Layer Property Flow (LPF) file to describe the property of the aquifer and flow, various source and sink files to record the recharge or discharge conditions, Preconditioned Conjugate-Gradient (PCG) (Hill 1990) file to describe method parameters during calculation when resolving the linear equations, Out Control (OC) file to define the result data format. All of these files and file path are put in a Name (NAM) file. When calculating the main program reads the model data by this name file and when head values converge, the model will output results into the files which defined in the NAM file.

Integration idea of groundwater model and GIS

In this paper the idea of "stable and dynamic" was adopted to set up the system of groundwater flow model and GIS (Fig. 1).

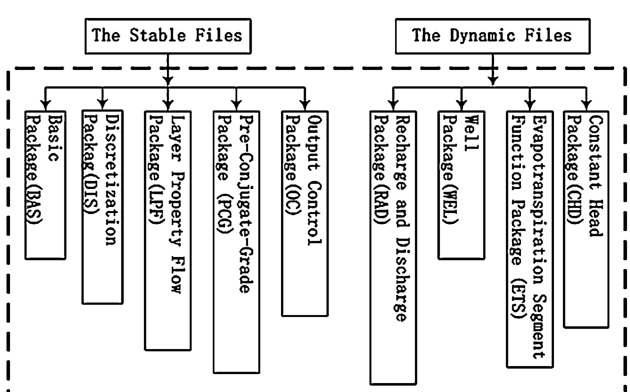

Fig. 1 File structure of groundwater model

The boundary, structure, parameters, calculation method and output data format of the model have been defined as the fixed files of BAS, DIS, LPF, PCG, OC respectively in the database. Especially, the parameters of the model including hydraulic conductivity, specific yield, storage coefficient, etc. should be calibrated before running the model to predict. By spatial analysis and attribute linking of MAPGIS and other GIS instruments (ARCVIEW) the original groundwater data information could be translated and read into above files.

As to the "dynamic" items of the groundwater model they were about the sources and sinks changing with time. In this system four packages were chosen to simulate recharge and discharge. Those packages were Well (WEL) package, Evapotranspiration with a Segmented function (ETS1) package (Banta 2000) which used a segmented function to describe the relationship between evapotranspiration and depth of groundwater, Constant Head (CHD) package and Recharge and Discharge (RAD was given as its name in this paper) package, which was added into MODFLOW-2000 based on the Recharge package. With RAD package the precipitation or irrigation recharge to all aquifer layers and the discharge from all aquifer layers could be simulated synchronously. Figure 2 is the process when adding the RAD package to calculate the groundwater flow. In the source code of MODFLOW-2000 each package is corresponding to a Unit Number. The sixth Unit Number in original source code was empty. So the RAD package was added as the IUNIT (6) and this package file could be read and entered into the entire calculation process.

Perennial data of sources and sinks were put into database. If selecting the starting time and the predicting time of simulation the relative data could be used to run the groundwater model.

Technical realization of integration groundwater model with GIS

MAPGIS was a kind of GIS developed by China Geoscience University (Wuhan) with Chinese language (Jiang and Lu 1999). It has powerful functions including spatial data collecting, storing, searching, analyzing and displaying as a picture and it can manage and query picture and professional data as a whole. Its function set is so abundant that the user can develop on the base of it. In this paper when dealing with the calculation of groundwater flow numeric modeling of the NCP, MAPGIS was adopted to realize the automatic calculation of sources and sinks model needed. Also it could realize the visualization display of the results.

The integration system of groundwater model and GIS was constructed based on the grid environment by

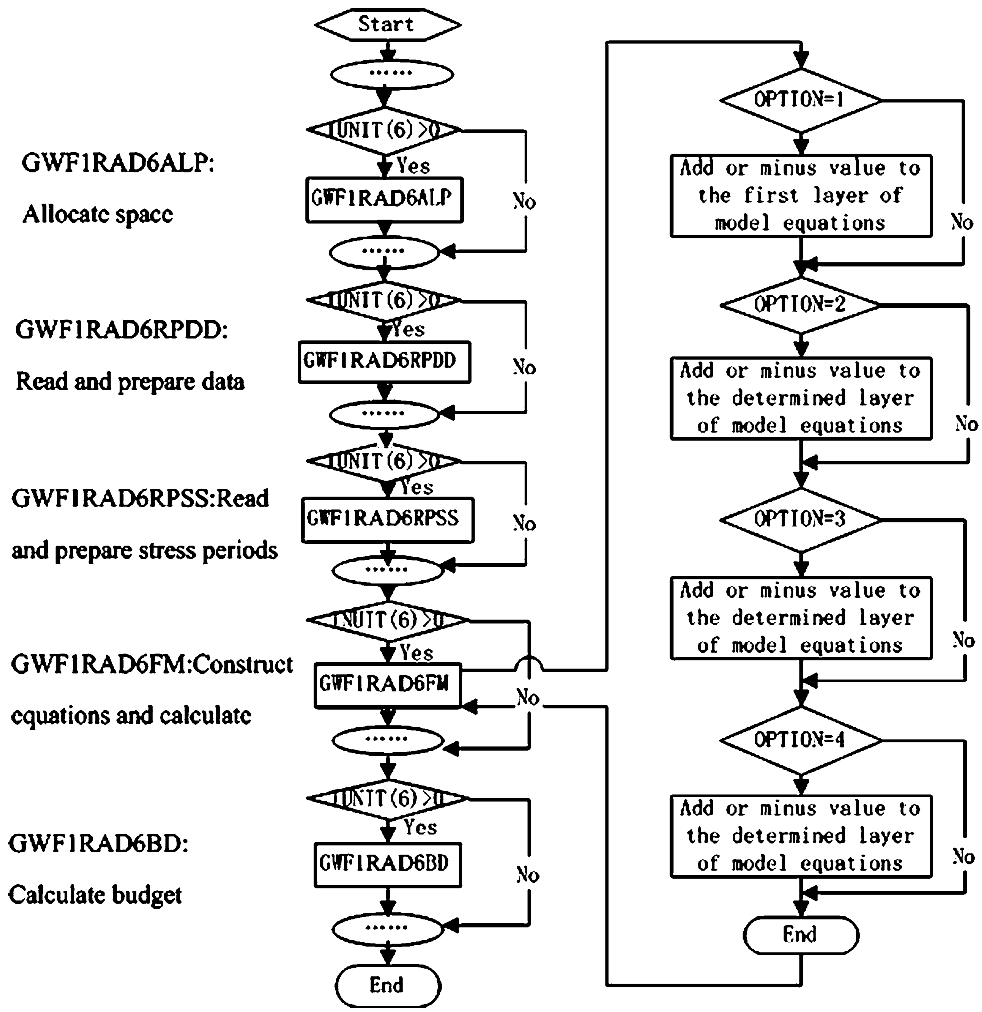

Fig. 2 Calculation flow when adding the RAD package

Web-service technology and it adopted multilayer network frame. There were four services including data obtaining service of single node, data congregation service of multi-nodes, calculation service of groundwater flow and visualization service of results.

The data obtaining service of single node was used to obtain the geology survey data of each province or city node for analyzing or disposing. Five nodes located in Hebei province, Henan province, Shandong provinces and Beijing and Tianjin city in China. This service had to get the data of each node to analyze (Fig. 3). All kinds of GIS techniques—graph cutting and combining, creating point or line or polygon cover files, and at the same time combining the spatial picture data which were stored in the database as the format of MAPGIS with the attribute data to obtain the data formats which were needed by the model—were adopted here. The data congregation service of multi-nodes service was used to congregate the single node data to the center node and create series data files for the model. The center node was located in the center of national geologic survey of China (Zhang et al. 2006). There were two kinds of data in the original database. The spatial data included precipitation infiltration coefficient or leakage coefficient of river or irrigation return coefficient, etc. The attribute data included precipitation, transpiration, pumping discharge or river leakage, etc. To transform the original data into the data files of MODFLOW, we used the visualized program language such as Visual C, Visual Basic, etc. The data files of MODFLOW have a fixed format and each cell data of study area must be written into the files as two-dimensional array format. The third service—calculation service of groundwater flow was used to integrate the source code of MODFLOW which was modified and compiled in need of practice by Web-Service. User could run the model and get the result to visualize. Also the expressions of result data were realized using the computer program language by the last service. Especially, on the expression of head and drawdown of the study area the Kriging method of Surfer was utilized under the MAPGIS circumstance.

Above four services pronged the process of the integration system (Fig. 4).

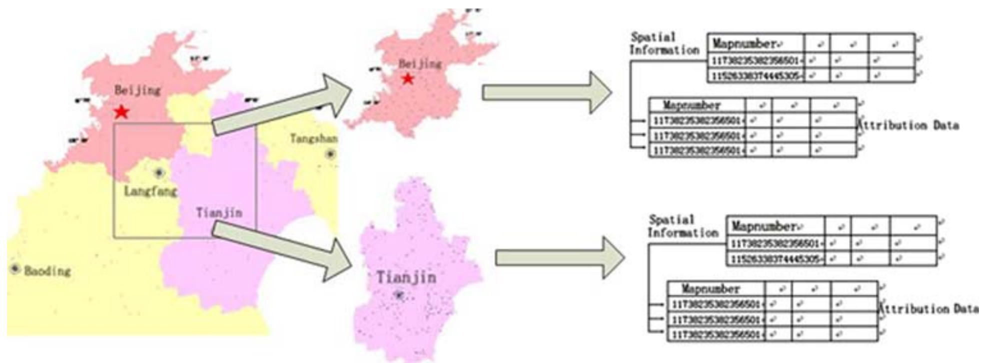

Fig. 3 Collecting the data of five node for analysis. Here it shows the data of Beijing and Tianjin were collected by the data obtaining service

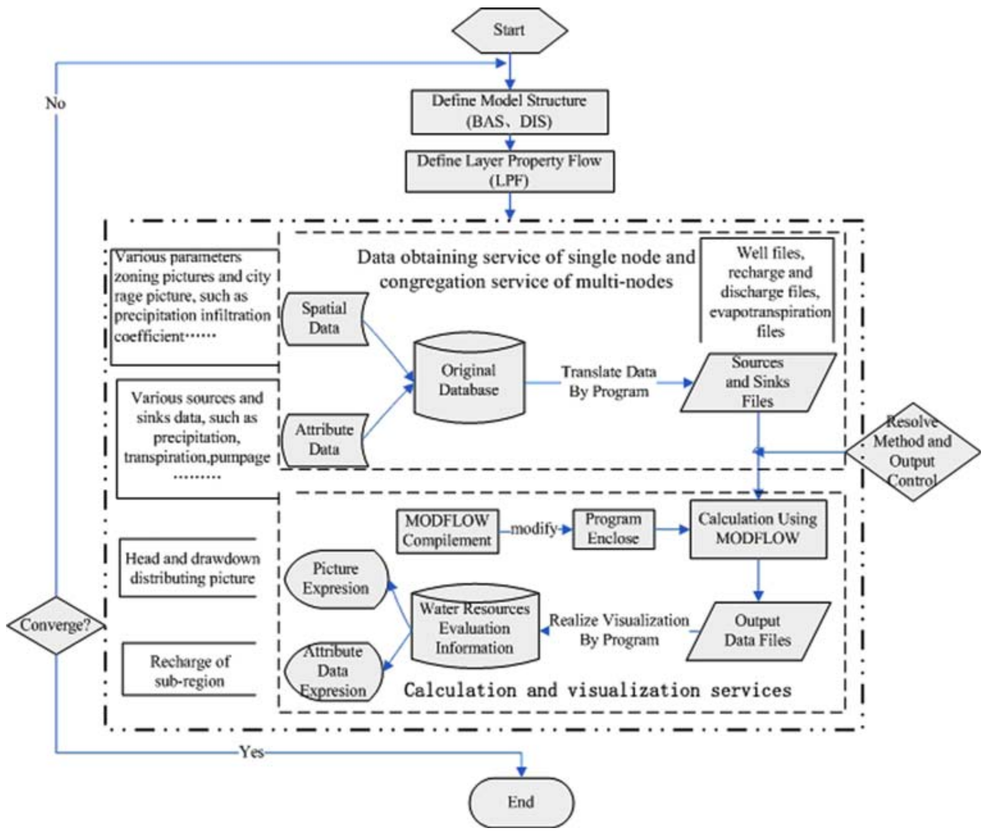

Fig. 4 Integration process of groundwater model and GIS

A case study of dynamic evaluation system of water resources for the NCP

Background of the NCP

The water resources per capita in China account for one fourth of the water resources per capita in the world and water shortage is outstanding. In North China more and more serious water problems such as the water table declines continuously and worsening of water quality occurs (Liu et al. 2001). However, the water problems in the NCP had a long history. In 1960s, many reservoirs were built in the west mountain of the NCP and drainage rivers were built in the east plain. It lead to the decline of water storage of the NCP and the flow-break of rivers. According to statistics of Lijin site of the downstream of the Yellow River, in 1950s the mean runoff was 460,00 $\times$ 10^6 m^3. In 1950s the mean runoff was 280,00 $\times$ 10^6 and 150,00 $\times$ 10^6 m^3 in 1990s. Because the surface water was dry, groundwater began to be discharged. Since 1970s, groundwater was discharged as major water supply to agriculture, industrial and domestic needs because of the dry climate and decreasing surface water. In the NCP, the proportion of groundwater to total water supply had increased from 53.9% in 1997 to 58.9% in 2001 and the increasing rate is 1% per year (Liu 2003). In recent years many environmental problems including water pollutions, land subsidence, land collapse and soil salinity became more serious than ever. The over-exploitation of groundwater changed the natural groundwater flow system. So, building a groundwater model using modern technology is benefit for the sustainable utility and management of groundwater.

Constructing the groundwater model of the NCP

Basic conditions description of the NCP

The NCP is located in the eastern part of the People's Republic of China. It reaches the Bohai Sea in the east and the Taihang Mountain in the west. The northern boundary of the plain is the Yanshan Mountain and the southern boundary is the Yellow River. The longitude is 112°30′–119°30′E with latitude 34°46′–40°25′N. The district includes all the plain area of Beijing, Tianjin and Hebei province and the plain area of Henan and Shandong province in the north of Yellow River. The overall area is approximately 140,683 km^2 (Fig. 5). The landform is a typically plain landscape and the elevation is less than 100 m. Topography inclines form north, west and southwest to the Bohai Bay. The slope gradient is 1–0.2% in the frontier mountain and 0.1–0.2% in the coastal plain. From the foot of mountain to the Bohai Bay it can be divided into the alluvial flood plain of the west part, flood and lake sedimentary plain of middle part and the alluvial coast plain of the east part (Fig. 6).

The climate of the NCP belongs to the continental climate. The perennial mean precipitation is about 500–600 mm(Fig. 7). The proportion of precipitation from July to September to precipitation of full year is about 75%. And the transpiration is about 1,000–1,500 mm. The proportion of evaporation from April to June to evaporation of full year is about 45%. In this study area there are Hai River catchment, Luan River catchment and Yellow River catchment. The Yellow River is the south boundary of the study area (Fig. 7).

Conception model and mathematic model

The unconsolidated sediments of Quaternary Q4 constitutes the main stratigraphy of this area. According to the features of the stratigraphy, it can be divided into three aquifers. The first aquifer includes aquifer groups of Holocene Qh4 with depth of 10–20 m, the upper Pleistocene Qp3 with depth of 50–70 m and the mid Pleistocene Qp2 with depth of 80–160 m. The second aquifer is the Lower Pleistocene Qp1 aquifer group with depth of 330–400 m. The third aquifer is Tertiary Qn stratigraphy (Figs. 8, 9, 10). Here the first and the second aquifers are defined as shallow aquifer and the third and forth aquifers are deep aquifers separately. These

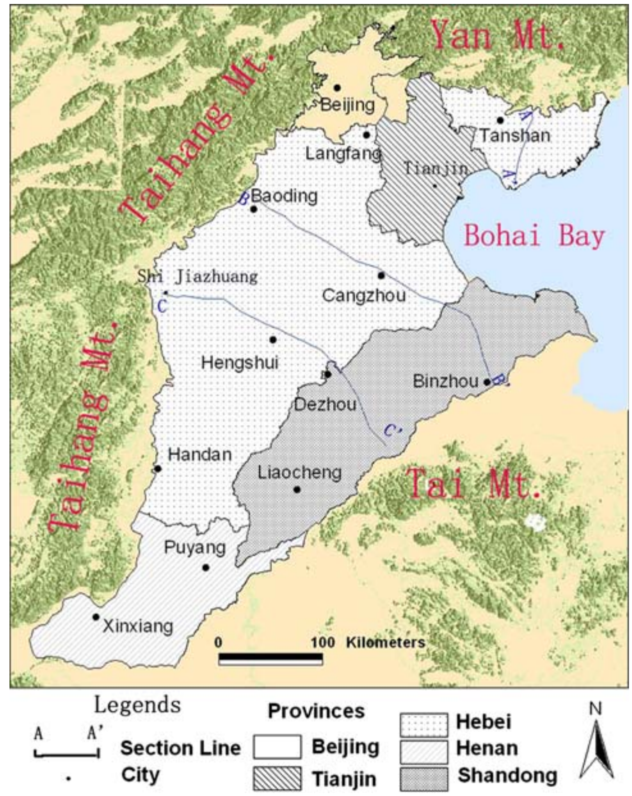

Fig. 5 Position of the North China Plain

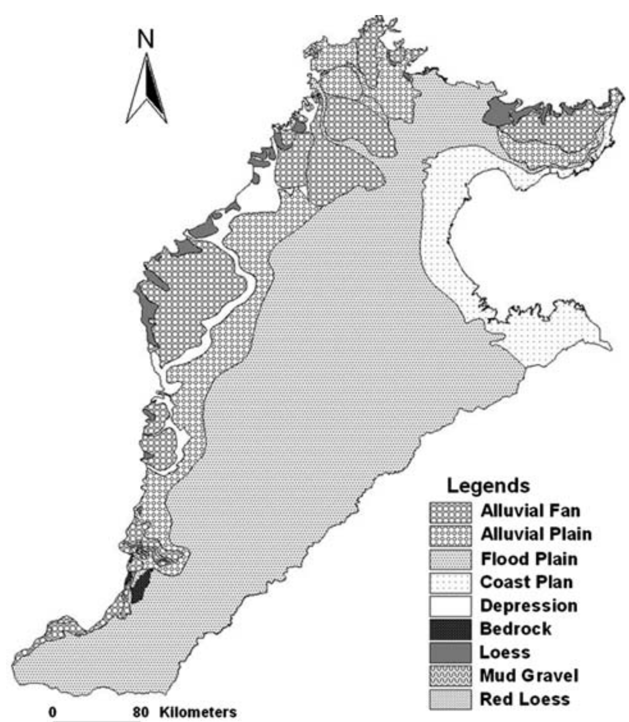

Fig. 6 Landscape of the North China Plain

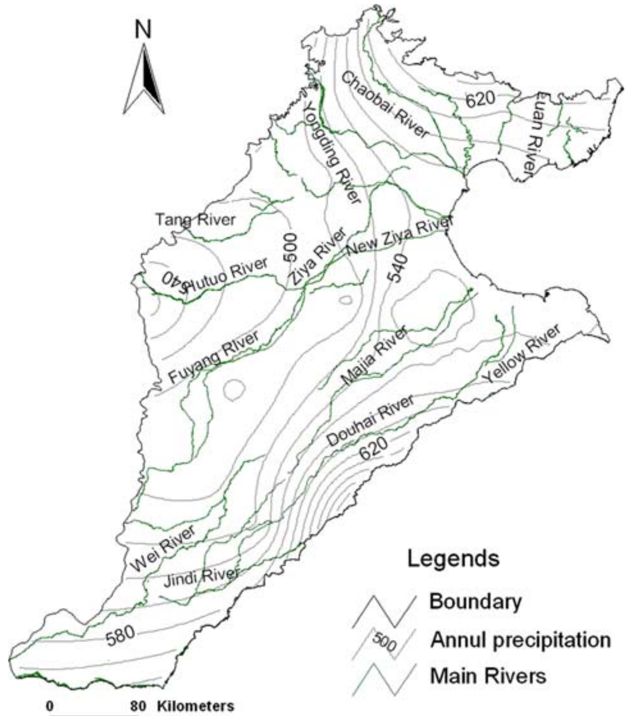

Fig. 7 Perennial mean precipitation and rivers. The perennial mean precipitation was made using the weather station data from 1975–2005

aquifers are located widely and they are thick, thus the horizontal direction flow is strong otherwise the vertical direction flow is slight. Because the recharge and discharge of this area change with time, which is the same with the water level, it is features of the transient flow. At the same time, parameters change with space, which is the feature of heterogeneous. As a result, the groundwater system of the NCP could be described as a conceptual hydrologic model which was a three layer, heterogeneous, horizontal isotropy, three-dimensions, transient flow system. In the north and the west of this conceptual model it received the lateral infiltration recharge of the frontier mountain. In the south it received the infiltration recharge of the Yellow River because the water table of the Yellow River was higher than the water table of aquifers. In the east the Bohai Bay was defined as the constant head boundary. The upper boundary was the phreatic water table and it received the precipitation recharge and discharged by evapotranspiration.

According to above analysis conditions the three dimensions, transient flow of groundwater can be expressed as flowing partial differential function (Xue 1997):

$$S\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right) + \varepsilon, \quad (1)$$

where K_x, K_y, K_z-hydraulic conductivity to x, y, z orientation separately (m/d); h-water head (m); S-storage coefficient of the aquifer under the water table (1/m); μ-specific yield; ε-source and sink item (1/d).

Combining with the initial conditions and the boundary conditions, the numeric model was constructed.

Numeric model

Model discretization Space The study area was discretized into 162 rows and 147 columns and the cells were the same regular rectangles. The total cell number was

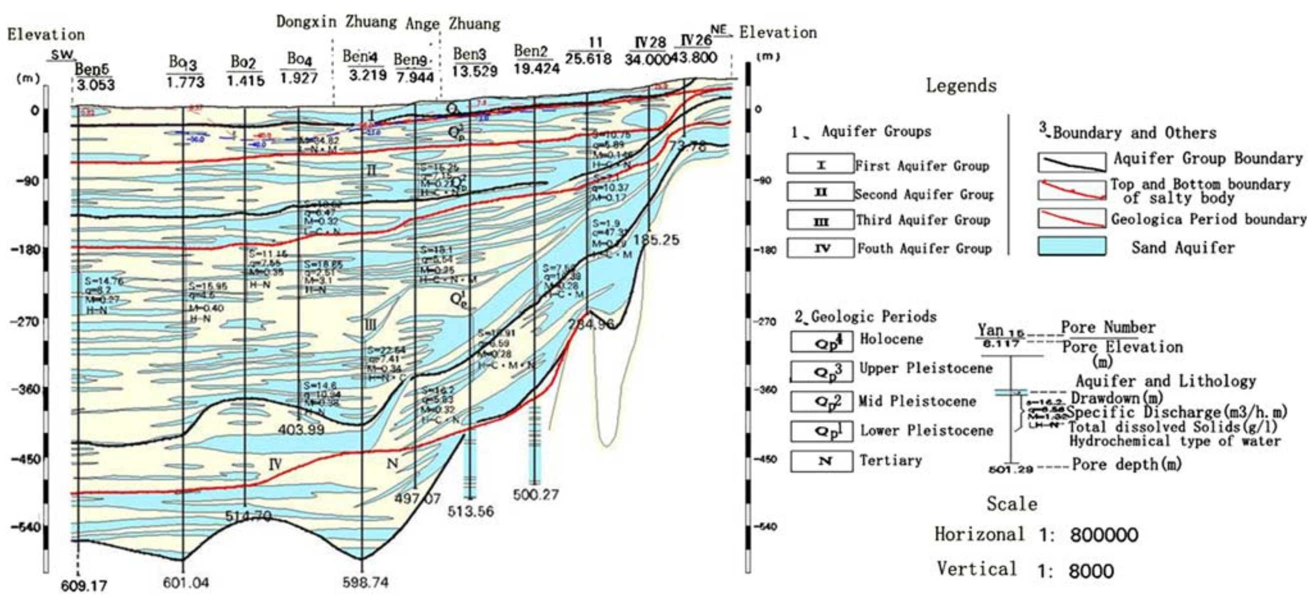

Fig. 8 Section plane to section line A–A′ in Fig. 5

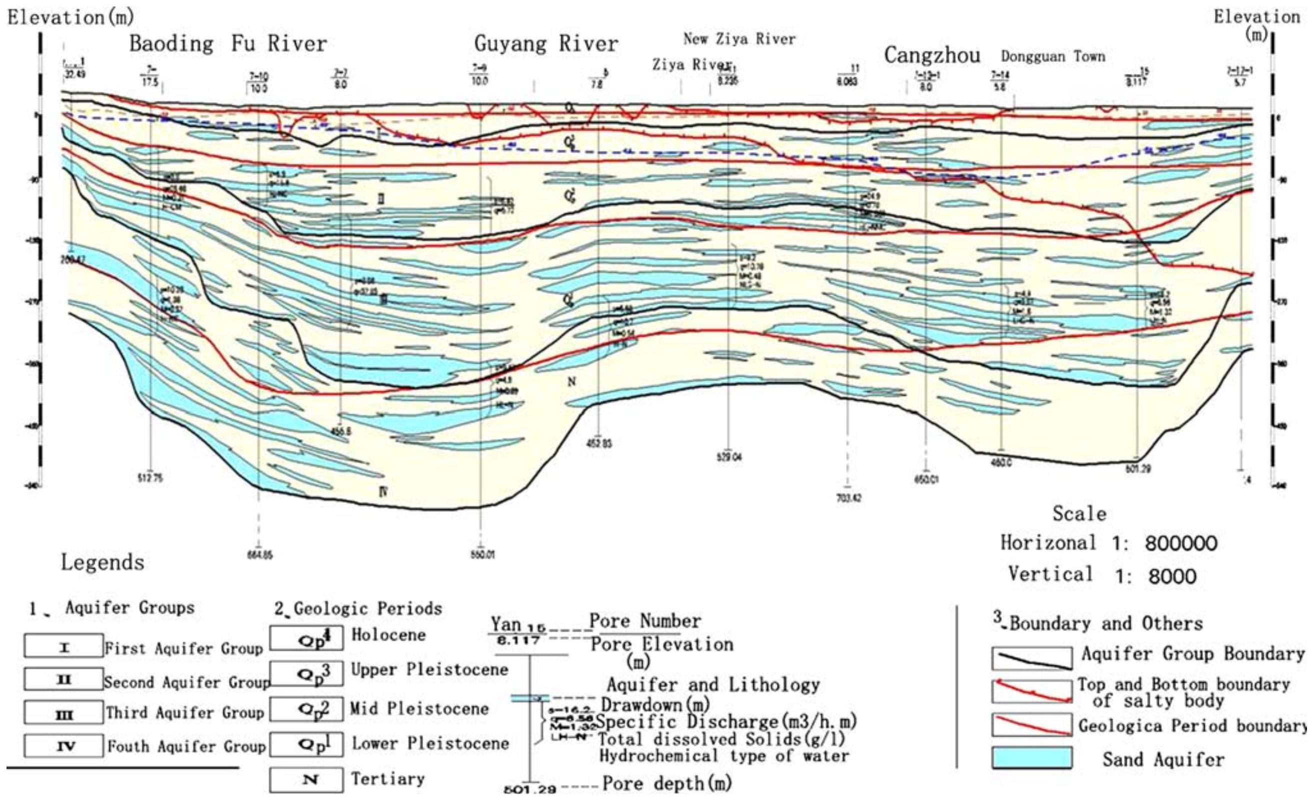

Fig. 9 Section plane to section line B–B′ in Fig. 5

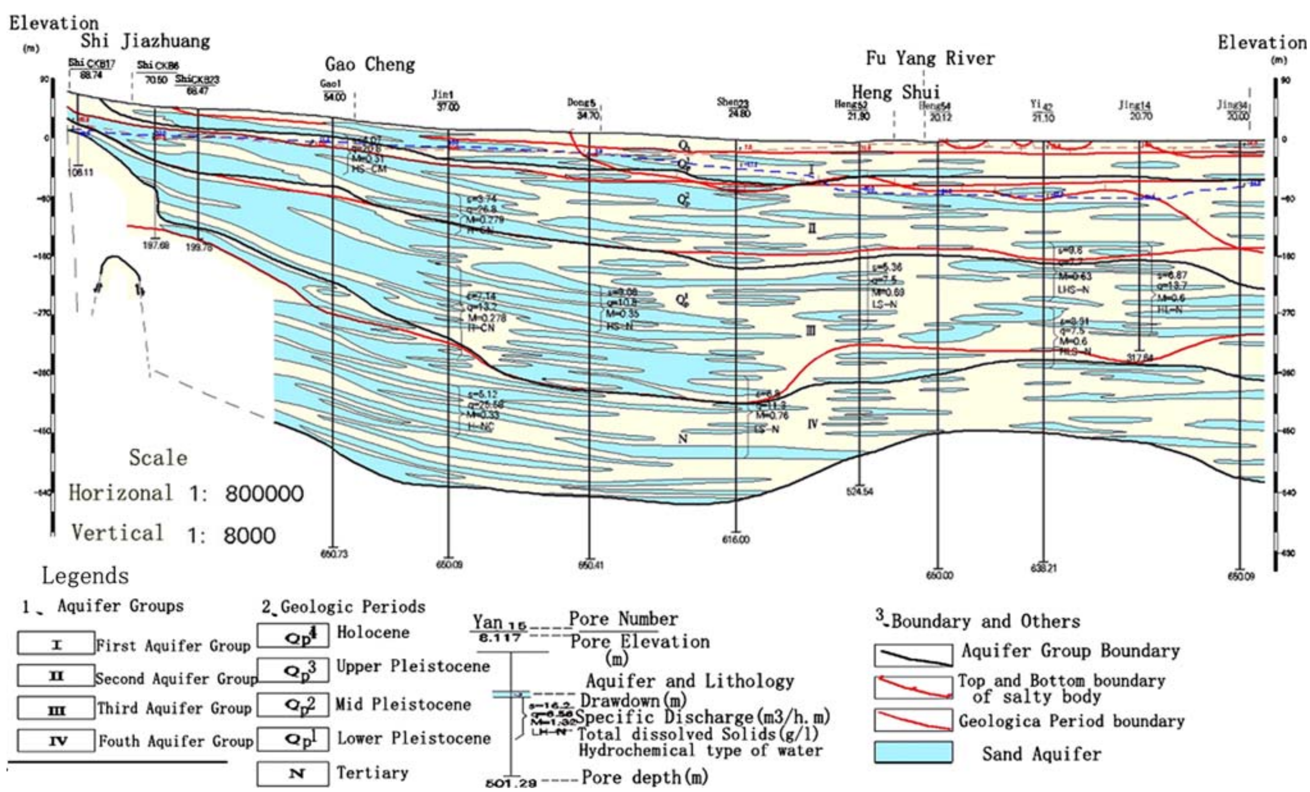

Fig. 10 Section plane to section line C–C′ in Fig. 5

23,814 and each cell size was 4 × 4 km. The entire model structure was a matrix of 162 rows × 147 columns × 3 layers (Fig. 11).

Time The simulation period was defined from 1 January 2002 to 31 December 2003. All kinds of budget data and dynamic water level data were provided by the five geology survey bureaus of the NCP. Each month was considered as a stress period so the total stress period number was 24. Time step was 1 day.

Solution conditions Initial conditions Based on the groundwater flow net which was supplied from North China Plain Project Groups, some water level points were obtained from flow net picture and these points were interpolated by Kriging method to gain the water level value of each discretization cell in the study area.

Boundary conditions The north and the west of the study area accepted the recharge of the Yanshan Mountain and the Taihang Mountain, so it was defined as the second flow boundary and the red arrows and the red lines were recharge direction and boundary location which accept recharge. Also the Yellow River of the south of the region was defined as the second flow boundary. The Bohai Bay was defined as the constant head boundary and the head is always 0 m from start to end time (Fig. 11).

Sources and sinks The recharge items of this area mainly include: precipitation, irrigation return, river leakage,

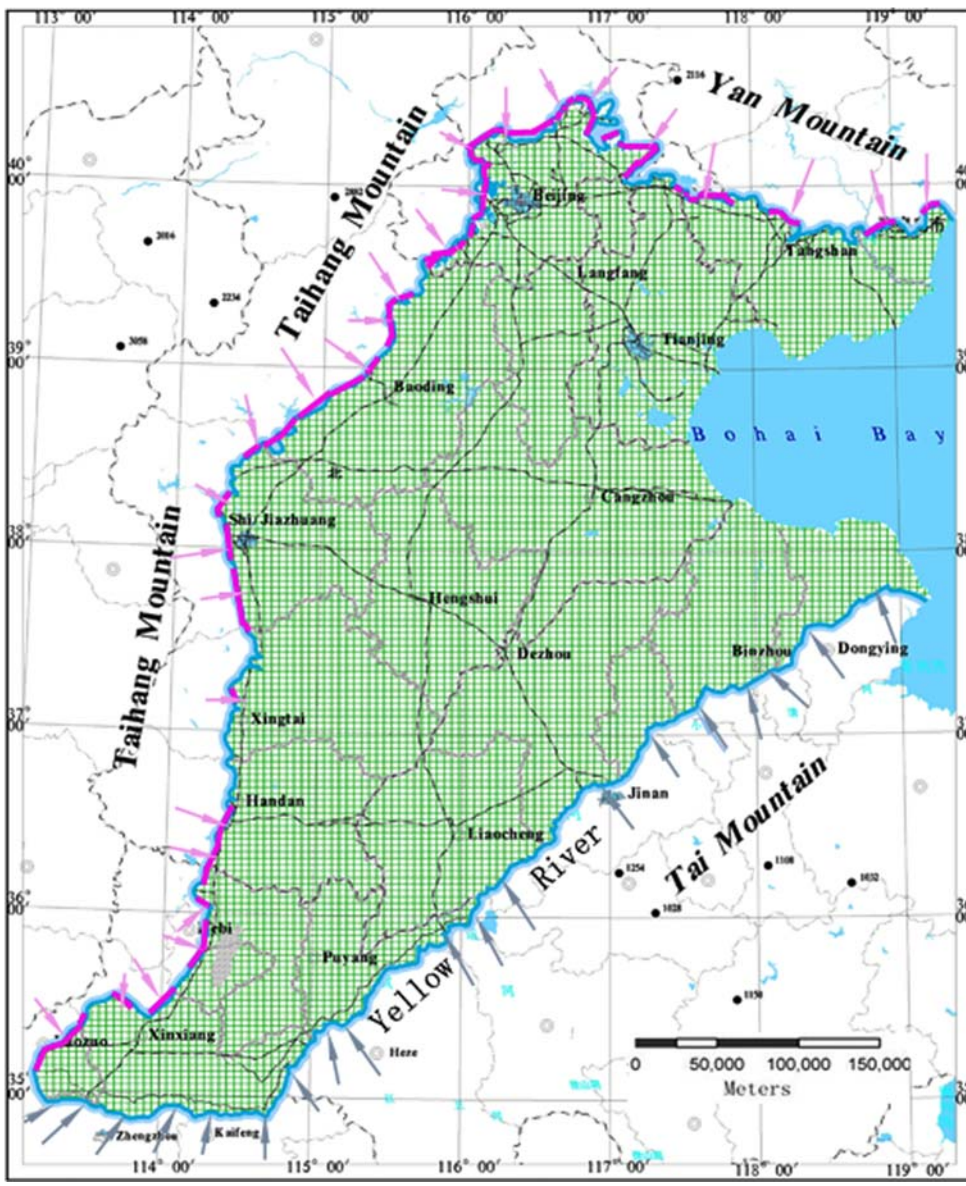

Fig. 11 Cell discretization of North China Plain groundwater model and boundary conditions

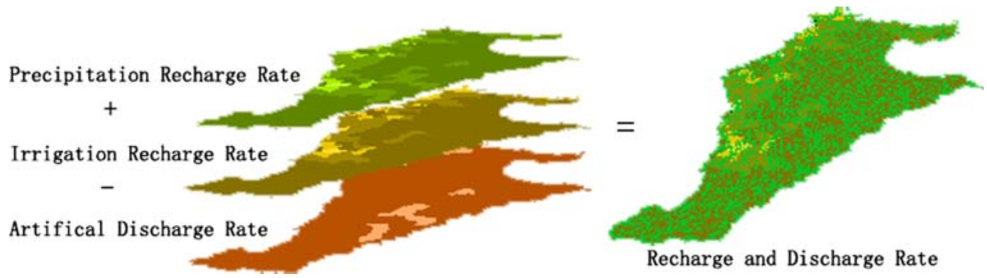

Fig. 12 Sketch map of recharge and discharge rate happened in the first layer

lateral runoff recharge from the mountain, boundary inflow of the Bohai Bay; the discharge items mainly conclude: artificial discharge, lateral boundary runoff discharge and transpiration.

When dealing with the sources and sinks, there were three ways: the first was to input data as the format of recharge rate of each aquifer. In this paper, the Recharge and Discharge (RAD) package was adopted to realize the data input of all layers. The RAD package can simulate problems under four recharge conditions: recharging to the top aquifer, recharging to the first aquifer, recharging to the certain layers of vertical column and recharging to all layers of the model. The fourth recharging pattern was selected here. As to the first aquifer (shallow aquifer) the precipitation recharge, the discharge of agriculture, industrial and domestic, the irrigation return were added together in each cell as the format of recharge rate or discharge rate (Fig. 12). Inflow was positive and outflow was negative. As to the second and the third aquifers (deep aquifers) only artificial discharge happened. In the NCP the water quantity was recorded by each county. That means a total number was corresponding to a county. So the water was averagely distributed into each cell of the county. The second kind data was to input data as the format of well flux in cells including the lateral recharge of frontier mountain and the river leakage recharge. Above two kinds of data were located in the active cells. The last was the transpiration discharge of the water table and it was mainly discussed here.

Transpiration is a significant discharge item during the water transportation process in the zone of aeration. Climate conditions, ground cover, the soil pattern and moisture, depth-to-water and other factors play an important effect on the groundwater system. In this paper, the Transpiration Segment Function package of MODFLOW-2000 (Banta 2000) was selected to calculate the discharge resulted by transpiration. The input data included the elevation of evaporation surface, the depth of the head below the ET surface, the maximum evaporation rate, the segment point PXDP and PXTM of the function (Banta 2000). The elevation of evaporation surface was defined by elevation of land surface. The maximum evaporation rate was got by the evaporation of water surface of each weather station in the NCP multiplying the experiment coefficient, 0.62. The extinct depth of transpiration was defined referring to lithology (Fig. 13). Meanwhile the relationship between the transpiration rate and the depth of the water table was made according to some experiment results (Table 1). In the geology survey report data of each province or city, the experiment relation between depth and evaporation was made (Fig. 14). Taking Hebei province as an example, in the frontier mountain plain the evaporation was very large with the depth of 1–2 m, decreased equably with the depth of 2–3 m, and it was very small with the depth of 3–4 m. In the middle and east part of the plain the evaporation was very large with the depth of 1–2 m, decreased equably with the depth of 2–4 m, and it was very small and stable with the depth of 4–5 m. Using this package the evaporation was 12,431 $\times$ 10^6 m^3 in 2002 and 2003 (Table 2).

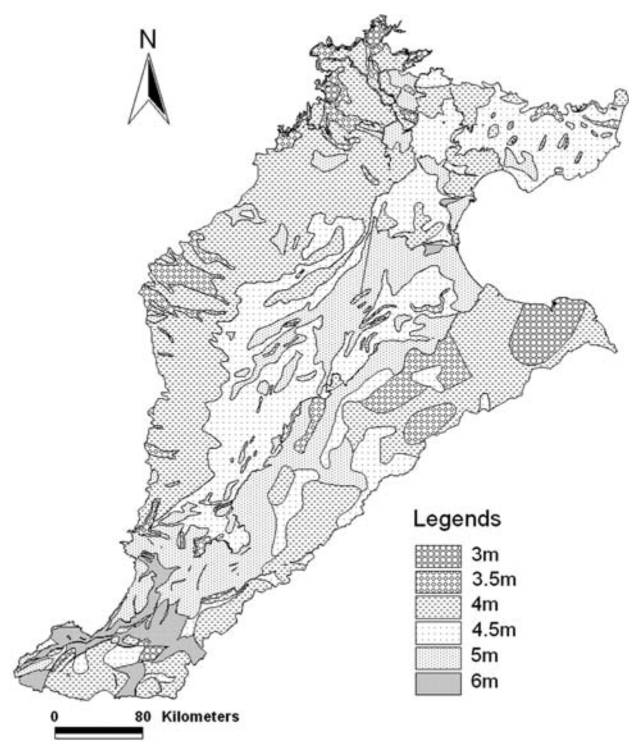

Fig. 13 Extinct depth of groundwater in the North China Plain referring to the lithology

Table 1 Parameters of segment point during define the relationship between the evaporation and the depth of groundwater

PXDP	0	0.046	0.16	0.31	0.62	0.92	1
PXTM	1	0.75	0.45	0.33	0.156	0.07	0

Calibration and identification of the model

During running the model the water level of ending time, which is called calculated head, must be compared with the observed head. Generally, the parameters and some sources and sinks of the model must be adjusted iteratively based on the hydrogeologic conditions combining with pumping tests. For a large regional model the calculated head must accord with the observed head (Figs. 15, 16). The flow net of unconfined aquifer or shallow aquifer displayed that the groundwater flow from the frontier mountain of north and west part to the plain of middle and east part and this was corresponding to the topography. In some region of frontier mountain over-exploitation led to the groundwater funnel. For example, the groundwater level of Beijing funnel was about −5 to −10 m; the groundwater level of Ningjin-Boxiang-Longrao (NBL) funnel was about −10 to −20 m in the frontier mountain of east Taihang Mountain. In the north frontier mountain, the groundwater level of Fengnan–Ninghe–Fengrun (FNF) funnel was about –10 to −20 m. The flow net of Fig. 16 displayed the fitting flow net of deep aquifer. In the frontier region of Taihang Mountain, the deep groundwater was discharged less. The groundwater of Henan wasn't discharged. In the middle part of the plain, groundwater was over-exploited and it led to obvious groundwater decreasing cone such as Dezhou, Cangzhou and Tianjin. The groundwater level was about −60 to −90 m in the groundwater funnel region. As a result, the groundwater flowed to the region of groundwater funnel. Then 62 observation wells with their water level change dynamically were selected to compare with the calculated head to ensure that the dynamic changes were similar (Fig. 17). Finally, the water budgets during the simulation period were analyzed. The total recharge was 49,374 × 10^6 m^3, and the total discharge was 56,530 × 10^6 m^3, the difference was −7,156 × 10^6 m^3 (Table 2).

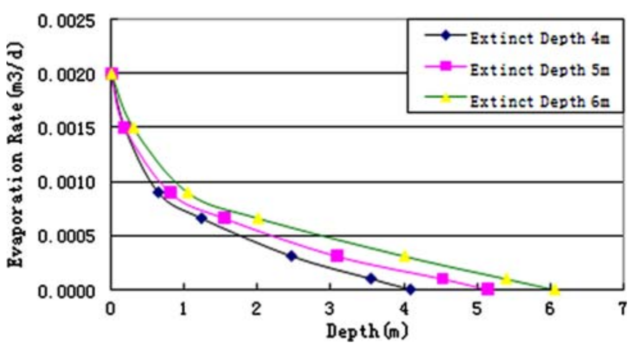

Fig. 14 Relationship between the evaporation and the depth of groundwater when the maximum evaporation rate is 0.002 m^3/day. Here 0.002 is an example. As to different maximum evaporation-rateion rate the relationship can be determined by the parameters in Table 1. And it shows the relationships of three extinct depth of evaporation: 4, 5 and 6 m, respectively

Application of the integration system of groundwater model and GIS

In practice, according to the natural factors, social production and national planning administrator can update the

Table 2 The total budget of groundwater system of North China Plain

Budget items	Shallow aquifer		Deep aquifers		Aquifer system
	Quantity (10^6 m^3)	Percentage (%)	Quantity (10^6 m^3)	Percentage (%)	Quantity (10^6 m^3)
Recharge					
Precipitation infitrition	34,220	75.15	0	0	34,220
Lateral	2,912	6.39	995	25.92	3,907
Agriculture return	7,200	15.81	0	0	7,200
River leakage	1,203	2.64	0	0	1,203
Aquifer leakage recharge	0	0	2,844	74.08	2,844
Total	45,535	100	3,839	100	49,374
Discharge					
Evapotranspiration	12,431	24.71	0	0	12,431
Artificial discharge	35,035	69.64	6,220	100	41,255
Aquifer leakage Discharge	2,844	5.65	0	0	2,844
Total	50,310	100	6,220	100	56,530
Budget difference	−4,775		−2,381		−7,156

Shallow aquifer refers to the first aquifer and deep aquifers refer to the other two aquifers

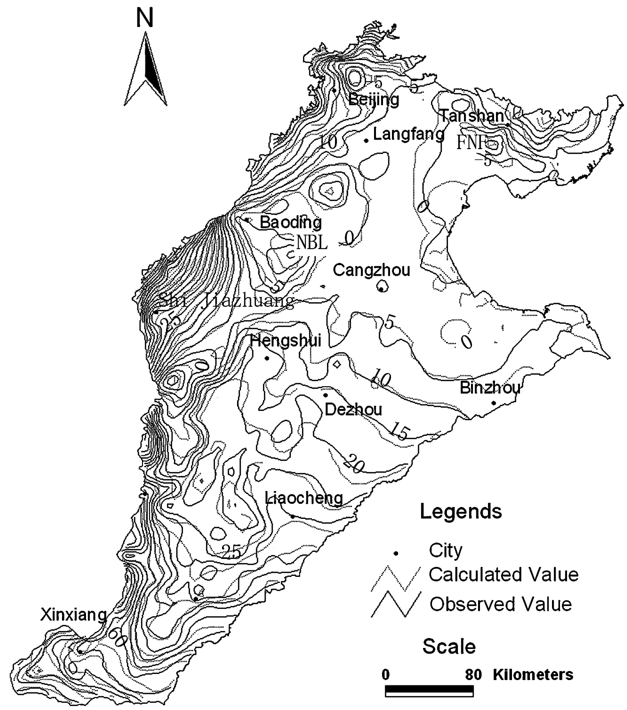

Fig. 15 Fitting graph of observed head and calculated head of unconfined (shallow) aquifer of the North China Plain in December 2003

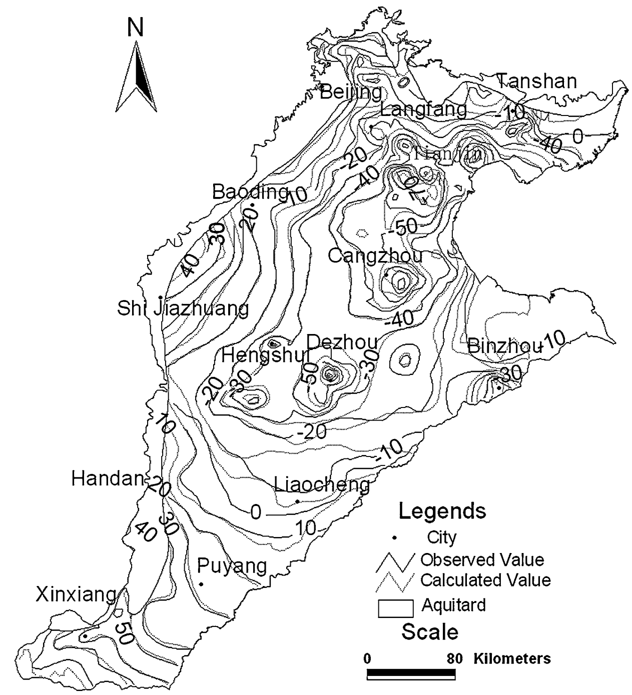

Fig. 16 Fitting graph of observed head and calculated head of confined (deep) aquifer of the North China Plain in December 2003

data of sources and sinks of the database which is needed when the model running so that the user can predict the head and drawdown of this area in the future. Also the user can calculate the recharge of sub-region. The administrator of each province or city of the study area put some original data as fixed format into the database. Then the user can run the model to evaluate or predict. By setting the parameter, user can check the water resources status of different time of different aquifer of this area. Beside of head and drawdown, the user can select a sub-region to check the total recharge in the future. For example, an internet interface of groundwater flow net as shown in Fig. 18.

Conclusions

To construct the groundwater flow model using the source code of MODFLOW, there were a lot of conveniences to integration with the GIS system. On the one hand, the user could modify old packages or add new packages to resolve groundwater problem under different hydrogeologic conditions. On the other hand, the user could obtain useful information during the period of modeling to benefit for integration or visualization. In this paper, the groundwater flow model MODFLOW and MAPGIS were integrated together under the internet environment. The water resources evaluation database of North China Plain was established and modeling data based on MAPGIS of China were stored in the database. During the process of preprocess, the GIS technology was used to create the input files of the numeric model. After calculating the results including the head and drawdown were shown by means of GIS technology and computer language.

The integration system was applied to the NCP. The study area was generalized to a conceptual hydrologic model which was three layer, heterogeneous, horizontal isotropy, three dimensional, transient. On the basis of the conception model, a numeric model was set up. The model was calibrated through fitting calculated value with observed value. The results of model were in accordance with the practical hydrogeologic conditions. And the water budgets of North China Plain showed that the total recharge was 49,374 $\times$ 10^6 m^3, and the total discharge was 56,530 $\times$ 10^6 m^3 during the simulation period, the difference was $-7{,}156 \times 10^6$ m^3. This verified that the groundwater in the NCP was over-exploited and the water crisis is serious. For the shallow aquifer of the NCP the precipitation recharge was the main recharge source and it was 34,220 $\times$ 10^6 m^3 accounting for 75.15% of all recharge in 2002 and 2003. And the evaporation is the main discharge of shallow aquifer accounting for 24.71% of all discharge in 2002 and 2003. For the deep aquifers of the NCP artificial pumping is the major discharge. That was the main reason led to series of water environment problems. The detail of other recharge or discharge were listed in Table 2.

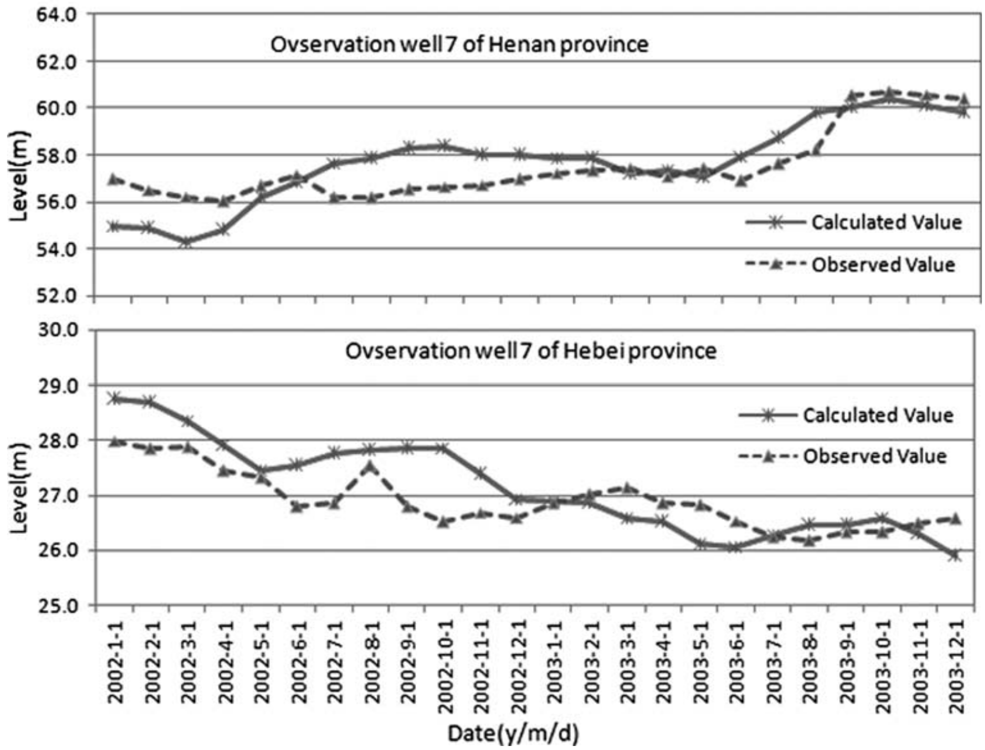

Fig. 17 Fitting graph of time series of groundwater level from Janaury 2002 to December 2003

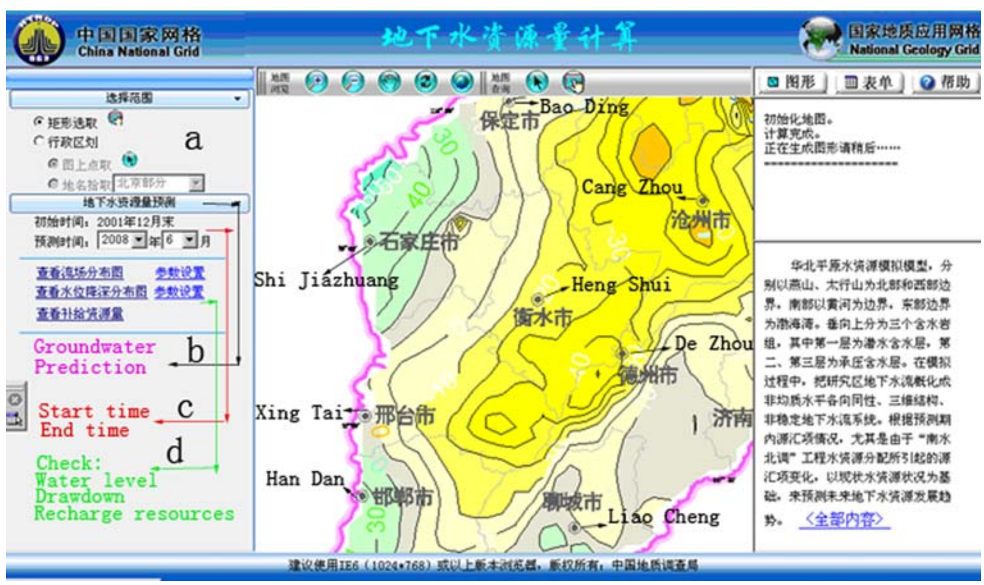

Fig. 18 Groundwater flow net of the integration system for Internet of Chinese groundwater evaluation. Rights reserved to China Geology Survey. Some interpretations were signed in the picture. Using this system user can select some region to calculate and display (**a**). Then select the start time (December 2001) and ending time (June 2008) run the groundwater to predict (**b**, **c**). After calculating the result can be checked such water level, drawdown and recharge resources (**d**)

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