Journal of Applied Sciences

ISSN 1812-5654

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Journal of Applied Sciences 8 (6): 966-974, 2008
ISSN 1812-5654

Development of a Three-Dimensional Numerical Model to Evaluate Groundwater Resource Flow of the Yuncheng Basin

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Abstract: In order to address groundwater resource sustainability, a conceptual three-dimensional, transient and anisotropic groundwater flow model comprising of six model layers was established to simulate the regional groundwater flow in the multilayered aquifer system of Yuncheng Basin of Northern China. Investigations indicate that the groundwater of Yuncheng Basin is extremely prone to over-exploitation and requires some quick and stringent attentions. The mean annual precipitation recharge, surface water discharge, irrigation infiltration and groundwater abstraction of sub-catchments of Yuncheng Basin are some of the parameters incorporated as input variable data. The model indicates that current well extraction rates are significantly less than annual groundwater recharge to the Basin. A model result for several scenarios tested by calibration and by adjustment of parameters like the hydraulic conductivity and storage yield indicates that extraction rates will be less than groundwater input to the Basin.

Key words: Groundwater resource, over-exploitation, environmental risk, numerical simulation, groundwater resource evaluation

INTRODUCTION

Yuncheng Basin is located in the south of the Shanxi Province comprising of Wenxi, Yuncheng city, Linyi and Yunji city and part of Xiaxian county, Xiang county and Wanrong region (Fig. 1). It is a rift Basin bounded in three sides by hills, in the north is E'mei Mountain, west is yellow river valley, while the east and south are bounded by Zhongtiao Mountains. Yuncheng Basin is an isolated Basin located on latitude 110°15' and 110°46' and longitude 34° 40' and 35° 38', with the total area of about 6100 km^2.

Groundwater flow models have been used in many studies to evaluate the effect of pumping in groundwater aquifer. In the 1980s, two-dimensional steady state finite element methods were used to evaluate the impact of groundwater pumping on water levels (Krohelski, 1986). However, two-dimensional steady state does not always accurately describe the important processes that happen in many aquifers systems. To correctly simulate the drawdown in aquifers, which in most cases vary temporally, three dimensional, transient models were developed (Hunt *et al*., 1998). There are 30 examples of land subsidence in China resulting from groundwater resources overexploitation (Han, 2003). Northern China possesses roughly 20% of the country water resources and 64% of land area (Zhen and Routray, 2002). China also receives its precipitation in only one -season -late summer, parts of Northwest have suffered from chronic severe water shortage in the face of rapidly rising demand (Amelia *et al*., 2007). The water table has fallen rapidly over the last decades, some cases over 2 m per year, rising pumping costs, resulting in land subsidence, saltwater intrusion and causing farmers to abandon thousands of wells (Kendy *et al*., 2003). Throughout Asia, urban groundwater mining is seriously impairing groundwater availability and quality, as well as causing disastrous side-effect (Okke, 1997).

With the intensity of human activities, the demand for water, especially for agricultural purposes, has increase rapidly and both surface water (including rivers, lakes and springs) and groundwater have been exploited (Hu *et al*., 2007). Dwindling water supplies have important implications for Northern China's agricultural sectors. Northern China, (especially northeast and northwest) is an important agricultural region. The north China plain alone produces roughly ¼ of China's grain (Zhen and Routray, 2002) and more than ½ of its vegetables and fruits (China National Statistical Bureau, 2004). Irrigation status has a positive impact on both yields and cropping revenue (Huang *et al*., 2002). Hence the future of water resources will impact both food security and rural income.

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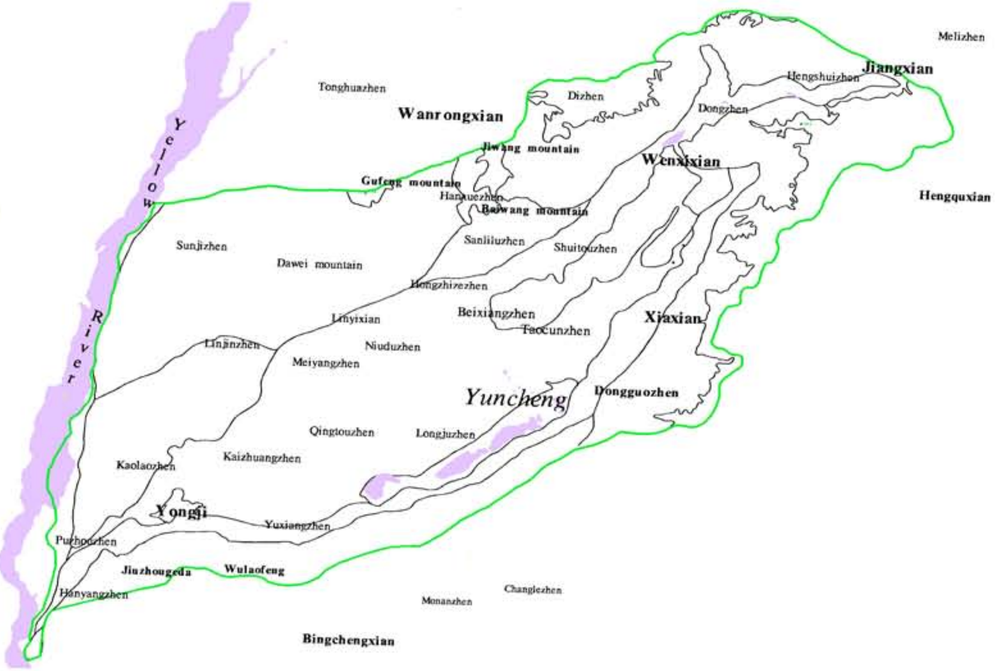

Fig. 1: Geographic location of the Yuncheng Basin

of the Yuncheng Basin, where groundwater is the main source of recharge. The consequences of Undue abstraction of groundwater among all are land subsidence, structural cracks and host of geological deterioration. Overdrawn of groundwater increased effective pressure on the rock layer, which resulted in the soil layer been compressed, thereby leading to the surface ultimately been subsided, causing a lateral structural fracture which can wreck havoc on the study area. An immediate simulation of the entire groundwater systems of the area has become a priority so as to establish a model, to predict the occurrence of the groundwater flow, especially in quantity, its exploitation and for effective and efficient management of the whole system for optimum production. The pattern of water resources exploitation has had a direct impact on the area of the delta oasis down stream of the Heihe river Basin, where the Heihe River is the main source of recharge. Interactions between surface water and groundwater have gained more and more attention (Sear *et al*., 1999; Sophocleous, 2002; Rushton, 2003). A careful study of the dynamic interaction between surface water and groundwater will provide some guidelines for reasonable water resources exploitation and prevention of regional ecological environment from further degradation (Hu *et al*., 2007).

Issues associated with water quality are beyond the scope of this report, but warrant some mentioning, since they are present in the study area. The impact of high-fluoride groundwater on human health in Yuncheng Basin, Shanxi Province, Northern China, has been a major concern for environmental and medical scientists for decade (Zhang, 1993; Cao *et al*., 1997; Lu *et al*., 2004). The results of hydrological survey show that the shallow groundwater in an area of over 3,156 km^2 at Yuncheng contain fluoride higher the Maximum Concentration Level (MCL) concentration (1.0 mg L^{-1}), occupying 50.8% of the total Basin area (Gao *et al*., 2007). In Linyi County where endemic fluorosis is the most serious, there are 13 villages where 22% of villagers have lost labor capability due to fluorosis (Gao *et al*., 2007). Also Wang *et al*. (1996) in his own research posited that superficial groundwater of Datong Basin (Northeast, Shanxi), is the main cause of groundwater pollution in the area. Since 1990s, under the impact of over-exploitation of groundwater, intrusion of the saline water from the salt into the shallow aquifers to its north has been observed (Yun, 2001).

In view of the heterogeneous nature of the Yuncheng Basin, its characteristic geological and hydrogeological conditions, the water-use demand and resource over-exploitations, it is of pertinence to develop a three-dimensional numerical model to evaluate the groundwater resource of the entire Basin.

The purpose of this research is to develop an understanding of groundwater sustainability under current aquifer conditions. Secondary objectives include: evaluating the potential of groundwater recharge and discharge rates, estimating sources and quantity of groundwater and ascertaining effect of current pumping on groundwater resources. To meet these goals, a three-dimensional numerical groundwater flow model would be developed to represent current aquifer conditions and to make limited predictions of sustainability under various scenarios. The results of this study are foundation for more robust evaluation of the groundwater system, which will dwell more on the transport aspect.

Using mean annual data as input parameter, the numerical flow model was constructed using the software package GMS-MODFLOW (Harbaugh *et al*., 2000). The Yuncheng Basin flow model uses the MODFLOW recharge, river, flow and well packages. Large portions of the model were assembled using other software program (Alexandra *et al*., 2007). The simulated model would be calibrated tested and finally forecasted to appraise the groundwater resource flow of the Yuncheng basin.

CLIMATIC, GEOLOGICAL AND HYDROLOGICAL INFORMATION

Geological: Yuncheng Basin is about 6100 km^2 and about 1186 km^2 of it surface is covered with high hills and Mountain. The Mountain base spans from the northeast to the southwest direction, the south and east is the overlapping Zhongtiao Mountain, the height of the Mountains are between 1200 and 1900 m. Zijing, Jiwang, Gufeng Mountains etc. are bounded by the northeast, north and northwest edge of the Basin. The Mountains range between 1100 and 1400 m in altitude and all spanning towards the Basin.

The center of the Basin is plain and its surface elevation is between 340 and 450 m being higher in the northeast and lower in southwest (Fig. 4). The higher northeast belt comprises of Hougongyuan in Wenxi and Mingtiaogang in XiaXian, which is about 500 m in height (Fig. 3).

The lower place whose surface is in northeast is between Zhongtiao Mountain and shi-li-Changgang and full of water (saline) throughout the year, there are swampy and many small lakes in the south and southwest of Basin which is about 320 m above sea level.

One of the most distinctive geologic features of the Yuncheng Basin is the existence of salt lake (Gao *et al*., 2007); the major mineral phases of the salt lake are mirabilite ($Na_2SO_4.10H_2O$), halite and astrakhanite ($MgSO_4.Na_2SO_4.4H_2O$) (Gao *et al*., 2007).

The study area (Fig. 1) is completely firm strata. The outcrop includes Archaean Eon, old Proterozoic, Epiproterozoic, Old Paleozoic, Era, Neopaleozoic, Mesozoicera and Cenozoic tertiary and Quaternary.

The Basin as characterized of Shanxi province forming part of the qilvhe Mountain form structure. The eastern limb is influenced by the east and west Qing Mountain structure zone, the stress of the structure zone is complex as shown in Fig. 2. The Basin structure is classified into two, firstly; the New Hauzia structure zone: the layer of this Basin is yellow river suburb zone, extending to the southwest of Zhongtiao Mountain along the yellow river valley and secondly; the Qilvhe arc folded zone; this Basin zone belong to the Qilvhe Mountain from eastern limb. There are several Xi type structure composed of uplift zone and hollow zone, they are; the Zhongtiao Mountain uplift zone and the Yuncheng hollow zone; GU Mountain, Jiwang Mountain, Zijing Mountain uplift zone. Yuncheng Basin hollow zone which is distributed through the entire study area, from the northeast to the southwest, the subsidence is low in the northwest and high in the southeast and in the center is Yuxiang Anyi. Mingtiaogang horst. There is a fault in the scarp of the mingtiaogang, it goes up and its two sides are inverted. The Qushui river valley Graben, the Qingling river valley Graben, which is formed in the middle of the southeast of the Qingtiaogang fault and the northwest of the edge of the Zhongtiao Mountain and kaolao fault ascending to the northeast and descending to the southeast. Gu Mountain, Jiwang Mountain and Zijing Mountain uplift zone which is 20 km wide, the Zhongtiao Mountain uplift zone with a large break in front and this being the lowest place.

The Basin is basically a closed one, except the area where the Fenhe River runs across. Groundwater only flows within the area. There is very thick loose sediment in the Basin and several layers of groundwater, the unconfined and first of confined aquifer are the mostly used and exploited part of the aquifers.

The unconsolidated formation in the Basin is composed of loose deposit from different time and origin, the lithology of the unconsolidated formation is different, henceforth, the distribution of the aquifer is irregular (Fig. 4). According to the aquifer distribution and hydrogeologic feature, the Basin interstitial water of the unconsolidated rock divides the aquifers into the unconfined/confined and confined aquifer. The phreatic recharge, precipitation, channel infiltration, irrigation seepage, reservoir infiltration and lateral recharge are the main sources of recharge to the unconfined aquifer, while, artificial pumping and the leakages between confined aquifer and aquitard constitute main discharge. Artificial pumping remains the major discharge source in the confined aquifer and cross flow between unconfined and aquitard are recharge source.

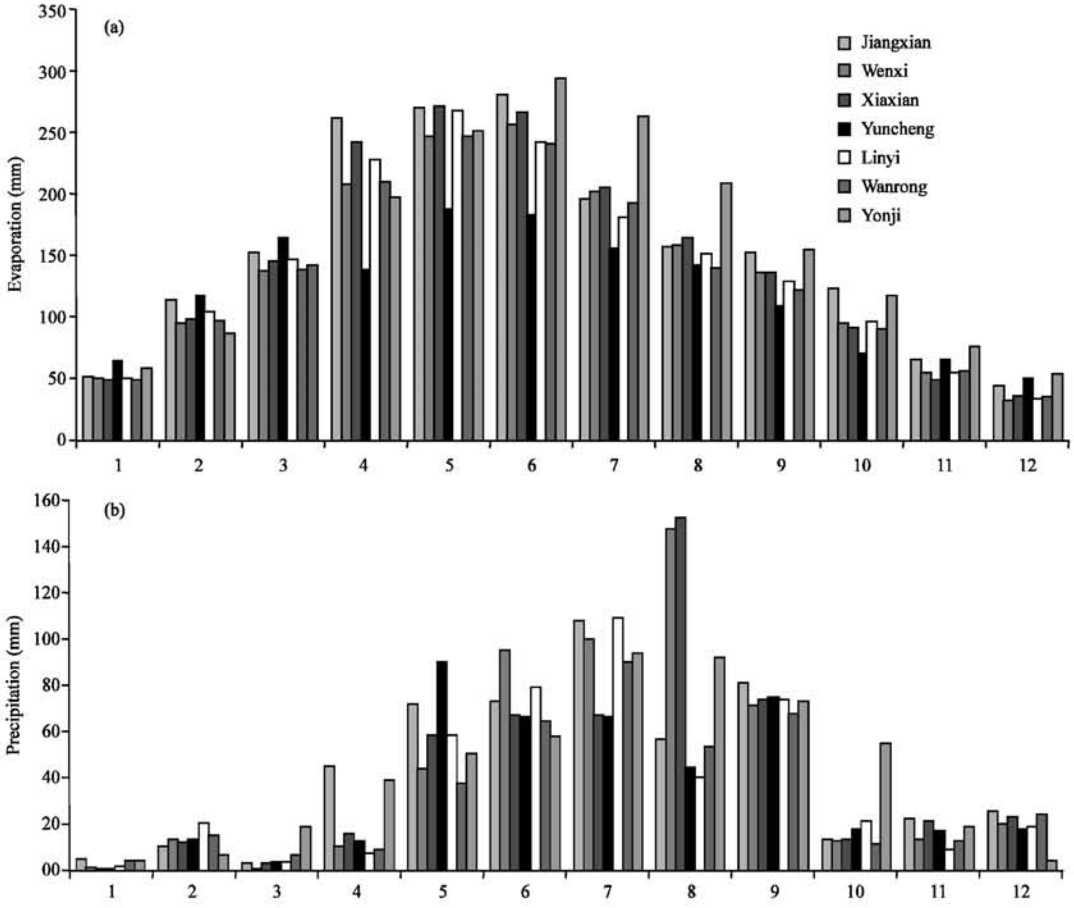

Fig. 2a,b: Mean annual evaporation and precipitation for Yuncheng Basin

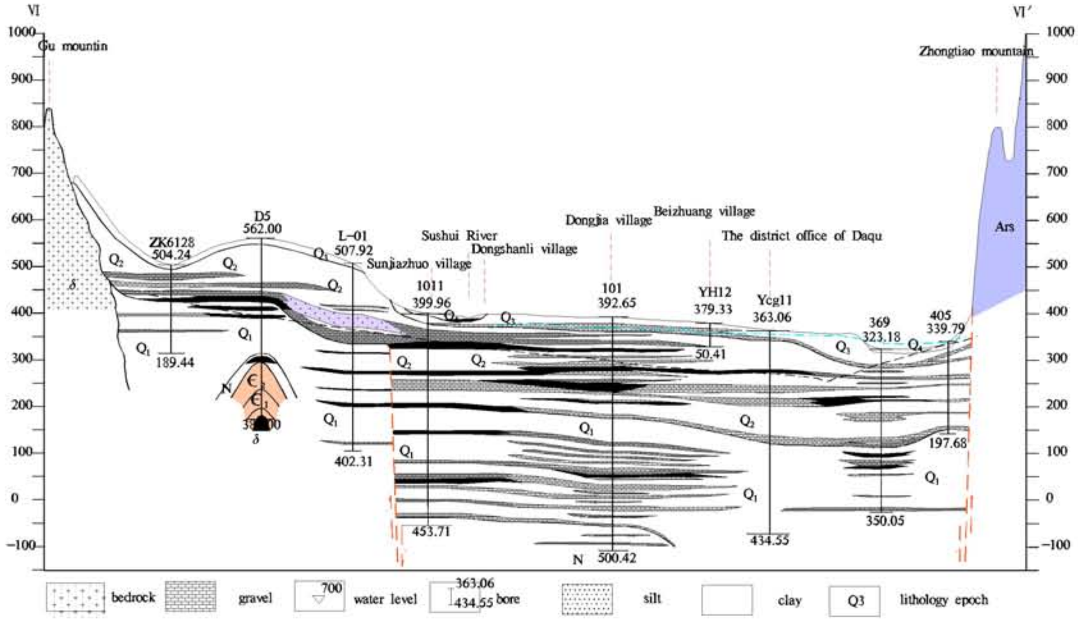

Fig. 3: Hydrogeological cross section of the Yuncheng Basin

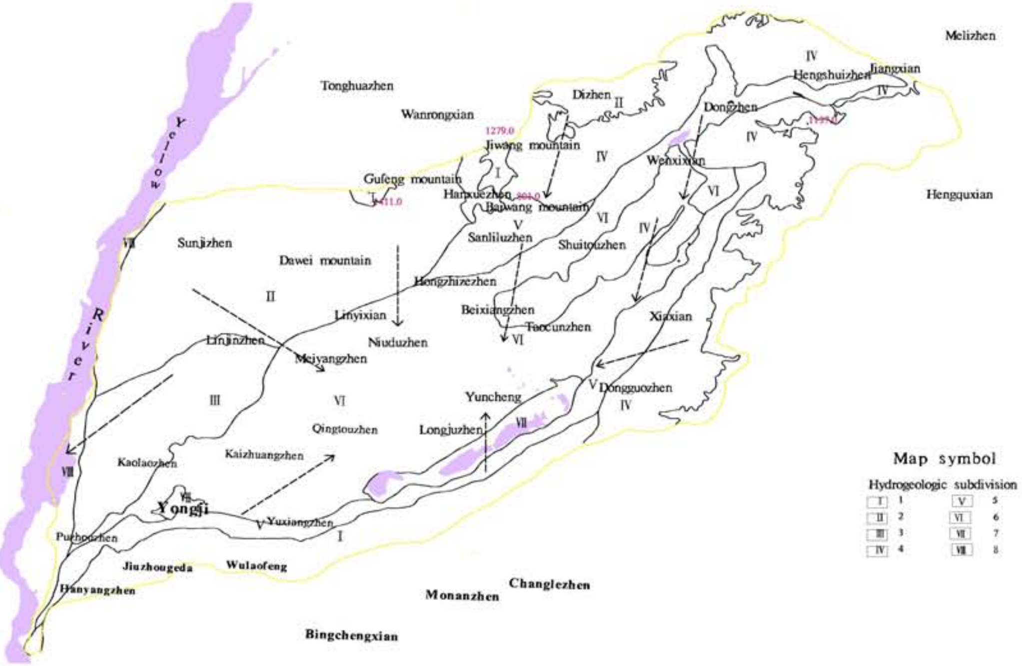

Fig. 4: The Yuncheng Basin depicted as a conceptual model, I-IV: Hydrological Zones, I: Bedrock; II: Highland III: Hilly loess region IV: Piedmont plain; V: Alluvial plain; VI: Salt lake; VII: Boundary of the study area; VIII: Flow path of groundwater; IX: Boundary of different landforms; X: Delineated frontier of saline water intrusion

The landform is different, from the north to south in the area are: Lvliangshan (Mountain), Fenhe (valley), Emei (tableland), Sushui (Basin), Zhongtiao (Mountain) and Yellow River (valley) and so on.

The climate: The climate is warm temperate and dry zone, half dry continental subjecting to monsoon climatic situation influence throughout the year. In spring (Match~ May), with lots of warm wind and little rain. The summer (June ~ August) is characterized with east wind, damp and high temperature, much turbulent rainfall with hail. Autumn (September~ November), is characterized with relative low humidity, the winter (December February) is dominated with north wind, dry-cold breeze with little rainfall and snow.

Due to the influence of climate, topography and latitude, the annual rainfall distribution is not uniform. There are many areas where the amount of rainfall alternates due to topographical fluctuations. The Mountain range arranges to the northeast or northeast direction, water vapor colliding with the Mountain serves as obstacle when it enters the Basin from the south and southeast, it goes up, causing decrease in rainfall from southeast to the north and northeast. Also for geographical reasons, the rainfall increases with altitude the higher Mountainous areas have higher precipitation than the lower or the lee face of the Mountains.

The average precipitation between 1956~2000 is 527.5 mm the rainfall distribution is greatly fluctuating throughout the year. in the flood time (June~ September), the distribution is about 60~70% for the whole year, the maximum was 945.8 mm in 1958 and the minimum was 305.0 mm in 1997, depending on the climatic factor. The, rainfall quantity and distribution is sharply changing and it's gradually reducing from 750~500 mm along the direction from the northeast to the northwest. The average temperature of the place, over years (1956~2000) is 12.8°C, while the average evaporation for the same period is 1148.0 mm, which is higher than twice the average precipitation over the same period. The frost free period is about 207 days. The maximum precipitation for the whole year was 756.0 mm; the minimum was 305.5 mm, while the average was 563.6 mm (Fig. 2a, b), respectively.

Hydrologic and hydrogeologic conditions: There are two main big rivers, namely; Sushui River and Qinglong River, all are tributaries of yellow river, the watershed is being enclosed by Mingtiao Mountain, in the north is Sushui river, which is the biggest in the area, its sources from Chen cun gu in Jiang county, its length is 196,000 m and the drainage area covered is 5935 km^2, it flows through Jiang county, Wenxi, Xiaxian, Yuncheng, Linyi and Xuejia village in Yongji county into the Yellow river.

The Qinglong River which takes its source in Wenxi Tang Wang Mountain is 81,600 m in length and it flows through Wenxi, Xiaxian and Yuncheng into the salt lake (Fig. 4).

From the north to the southwest in the Basin are other features like: Tangli beach, Yazi pond, Yan Hu (saline lake), Beimen beach, Xiaochi, Wuxing lakes. The area covered by the Yan Hu (saline lake) is about 106 km^2 the Basin is covered with marshy, stagnant pool (backwater) with Yuncheng natural lake, Xihuayuan and Xushuichi as the biggest ones.

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The unconsolidated formation in the Basin is composed of loose deposit from different time and origin, the lithology of the unconsolidated formation is different, henceforth, the distribution of the aquifer is irregular. According to the aquifer distribution and hydrogeologic feature, the Basin interstitial water of the unconsolidated rock divides the aquifers into the unconfined/confined and confined aquifer. recharge takes place via infiltration of precipitation through fractured and the rock matrix (Gyau-Boakye, 2001). There are no known studies using direct measurement, water balance method, trace techniques, or empirical to establish recharge processes or to estimate recharge rates (Alexandra *et al*., 2007). The phreatic recharge, precipitation, channel infiltration, irrigation seepage, reservoir infiltration and lateral recharge are the main sources of recharge to the unconfined aquifer, while, artificial pumping and the leakages between confined aquifer and aquitard constitute main discharge. Artificial pumping remains the major discharge source in the confined aquifer and cross flow between unconfined and aquitard are recharge source.

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NUMERICAL MODEL

Conceptual model: Based on the hydrogeologic conditions of the study area, the groundwater seepage from Basin peripheral to the center, the soft deposition aquifer of Yuncheng Basin aquifer can be described as heterogeneous and anisotropic medium. The Basin groundwater could be formulated into a three-dimensional flow system (Fig. 4).

In this simulation, the basic collection of the materials made the model boundary as a specific flow boundary. The model recognition is depended on the annual mean precipitation and evaporation. Fewer dispersed exploitations can be disposed as square exploitation, while the centralized exploitations can be disposed as the actual exploitation quantities by the Well depth. The quaternary pore water in Yuncheng Basin is an integral groundwater system and the recharge is mainly from precipitation, runoff, base flow and irrigation. while exploitation, evaporation and leakages are main discharge.

Mathematical model: Based on the conceptual model of the Basin groundwater flow system, the three-dimensional mathematical model could be expressed as follows:

$$\frac{\partial}{\partial x}(k_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(k_y\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(k_z\frac{\partial h}{\partial z})-w=\mu_s\frac{\partial h}{\partial t} \qquad (1)$$

$$h(x, y, z, 0)=h_0(x, y, z)$$

$$h|_{B1}=f(x,y,z,t)|_{B1}$$

$$k\frac{\partial h\ (x,y,z,t)}{\partial n}|_{B2}=q\ (x,y,z,t)|_{B2}$$

where, k_x、 k_y、 k_z、 are hydraulic conductivities along the x, y and z -axis (LT^{-1}); h is the hydraulic head (L); w is a volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1}); μ_s is the specific storage (L^{-1}) and t is time (T). h_0 is initial hydraulic head (L); $f(x,y,z,t)|_{B1}$ is the first boundary; $q\ (x,\ y,\ z,\ t)|_{B2}$ is the second boundary. Equation 1 describes groundwater flow under non-equilibrium conditions in a heterogeneous and anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the coordinate directions. Analytical solutions of Eq. 1 are rarely possible except for very simple systems; therefore numerical methods must be employed to obtain approximate solutions. One of the most important ways is the finite-difference method, which is described in the continuous system. Equation 1 is replaced by a finite set of discrete points in space and time and the partial derivatives are replaced by terms calculated from the differences in hydraulic head at these points. The process leads to systems of simultaneous linear algebraic difference equations; their solution yields values of hydraulic head at specific points and times. These values constitute an approximation of the time-varying head distribution.

The modflow module of GMS 6.0 was applied to solve the above mathematical model in this groundwater resource flow evaluation. The entire study area was divided into 20856 rectangular cells units based on geological and hydrogeological conditions, the section

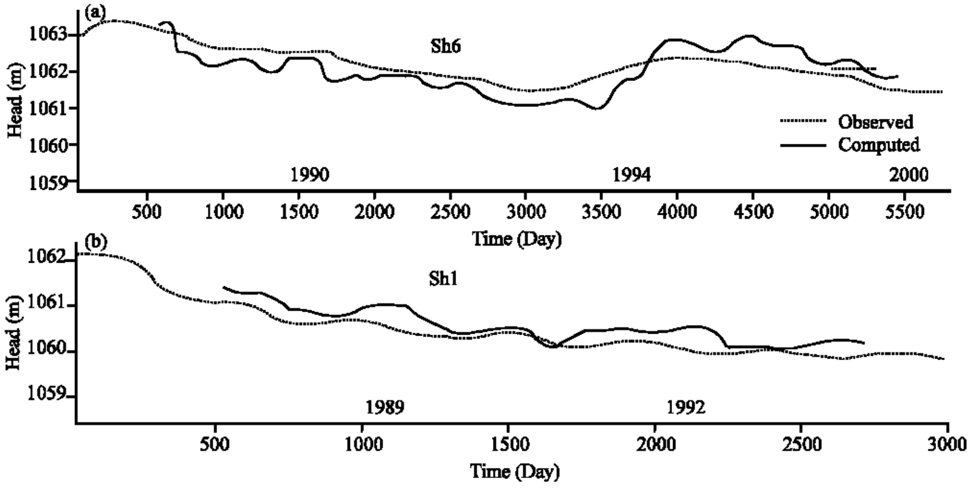

Fig. 5a, b: Comparison between observed and computed head values

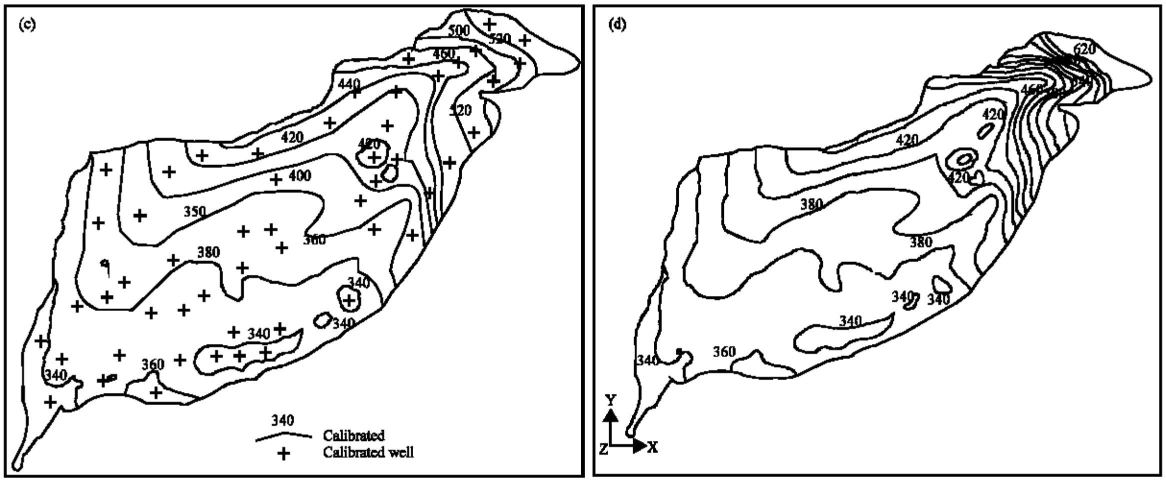

Fig. 5c, d: Comparison between the calibrated and the original model

was divided into 6 vertical layers and each unit area is 1.45 km^2, the length is 1044 m in x-direction and 1391 m in the y-direction and time steps 30 days was used for the simulation.

Model calibration and verification: Generally, model calibration and verification consist of three basic aspects: dynamic and water balance calibrations, verifications of the simulation and observation of flow field.

Initial flow field and time division: The water level data of 27 observation wells collected from 2001 to 2005, the initial water level of May 2005 was used in the calibration and the end of the calibration was July 2006. The model examination and prediction were integrated in this model, the model was predicted for another fifty four days which ended in January 2011 precisely. The hydraulic head, the specific storage and the specific yield were the parameters adjusted in this model before a well match could be achieved. For example, during the prediction period the change in the hydraulic head was just about 0.61 which confirms the applicability of this model.

Dynamic calibration and verification: Thirty observations well were considered, 12 for the first layer observation well and 18 for third layer observation wells for the fitting result, Fig. 5a-d, respectively. It was observed from the fitted curve (Fig. 5a, b), that the Basin model calibration was obtained when different between measured and calculated water level were minimized, available surface water flow record are matched to model-calculated Basin surface water flow and a water mass balance with little or no discrepancy was achieved (Fig. 5a-d, respectively).

Table 1: Showing the water balance result (×10^4 m^3/year)

Source/sink	Observed data	Computed data	Difference
Recharge	48273.48	48128.21	-0145.27
Discharge	51560.64	53165.35	-1504.71
Water balance	-03287.16	-05037.14	-1749.98

The aquifer parameter and the infiltration coefficient were confirmed. The boundary condition was calibrated by the method of correction, for its simplicity among other indirect methods. Firstly, the parameters were grouped according to hydrogeologic conditions and known pumping test data. The water head at each grid point were calculated with time using the numerical difference method. The calculated and observed head were also compared and the initial parameters were simultaneously adjusted until a reasonable match was achieved.

The observation data for a long period was not available for the Yuncheng Basin and wells observation data also varies with direction. From 2001 to 2005, the long term observation wells was used only in 2002 and concentrated on the north east of the Basin, this was not enough for a dynamic match of the whole area to achieve a perfect match.

DISCUSSION

There is a wide disparity between pumping and recharge in China, especially in the North, where pumping is outrageous and posing serious danger on the economic development of the region (Okke, 1997). In order to evaluate the overall groundwater resource and also evaluate the possibilities of any environmental hazard, geological exploration, meteorological data, strict adherence to programming principle of groundwater, considering the number of Basin and time -space distribution and so on, some salient observations were arrived at the Basin hydrogeological parameters such as; aquifer distributions, specific storage, permeability coefficient, storage coefficient, precipitation, phreatic water evaporation, infiltration recharge coefficient were confirmed through the evaluation of previous studies and literatures, borehole analysis, geologic and hydrogeologic studies as well as experimental data. From a thorough analysis of geological and hydrogeological conditions of the Basin, the conceptual model was developed and the 3D mathematic model of the groundwater flow in the Basin was also formulated. The 3D mathematical model of the groundwater flow was analyzed using the software GMS 6.0. The model recognition time was taken from May to October 2005; the model was calibrated, observed, forecasted and analyzed using the model recognition method. The model was analyzed based on three schemes; constant pumping conditions, the pumping yield increased by 2% in five years, also by increasing in pumping at Yunji Yellow River and forecasting the future groundwater level in five years using the pumping in the area.

Due to the current restriction on geological exploration in the study area, few wells observation data were available and a longer observation data would be required for a better precision and accuracy. Because of this limitation a further research is recommended with longer observation data which will improve the model matching and recognition for a better groundwater protection and management. Lastly the statistical department responsible for groundwater exploitation is not sufficient for expansion and detail data organization.

CONCLUSIONS

A three-dimensional Numerical model of six multi-layered aquifer with unit area of 1.45 km^2, strictly based on the geological and hydrogeological parameters of a typically closed Yuncheng basin, with annual mean rainfall of 563.0 mm and mean evaporation of 1148 mm, respectively, have been used to simulate the influences of change in groundwater head with time. Calculation from head have been compared with observed and show good agreement between estimated and observed values, Fig. 5a and b, respectively. A time series from serial number one to eighty six was calibrated and simultaneously observed and forecasted for another fifty four time series. The initial calibration time was May 2005 while the end time was January 2011. However, a complete data of May 2006 was used in the history matching and a well match was obtained (as compared in Fig. 5c, d, respectively) the hydraulic conductivity and the storage coefficient were both adjusted during the history matching, while the pumping rate was initially kept constant during the observation time and later increased by 2% in 5 years and also the pumping at Yunji Yellow River was increased respectively. The history matching, simulation observation and prediction were reasonable, thus, we can conclude that the developed numerical model has truly described the dynamic processes in the groundwater flow evaluation of the Yuncheng Basin.

ACKNOWLEDGMENTS

This study is financially supported by National Natural Science Foundation of China (40372111) and China Geological Survey (CGS.1212010634404).

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