地理学报(英文版) 2002年第12卷第2期

Groundwater regime and calculation of yield response in North China Plain: a case study of Luancheng County in Hebei Province

作者: JIA Jin-sheng YU Jing-jie

The groundwater table has been declining at a rate of 0.65 m/yr in Luancheng County since large scale groundwater extraction carried out in the 1960s. The drop of precipitation, substantial increase in agricultural output, variations of crop planting structure and construction of water conservancy projects in the headwater area all tie up with the decline of the groundwater table. On the basis of analyzing the hydrogeological conditions and the water resources utilization of Luancheng County, a three-dimensional groundwater flow model was developed to simulate the county´s groundwater flow through finite-difference method using Visual Modflow software. We divide the research field into four parts after analyzing the hydrogeological condition. Based on parameter calibration and adjustment using measured data, the hydraulic conductivity and specific yield were simulated. Using the calibrated model, we analyze the agricultural water saving potentiality and its influence on the groundwater. The results are as follows: (1) if we decrease the amount of water extracted by 0.14?108 m3, the average groundwater table of the five observation wells in December will rise by 0.33 m; (2) if we decrease the water by 0.29?108 m3, the average groundwater table of the five observation wells in December will rise by 0.64 m; and (3) if we increase the water by 0.29?108 m3, the average groundwater table of the five observation wells in December will decline by 0.45 m. So we can draw a conclusion that controlling the agricultural water use is an important way to prevent the decline of groundwater table.?

Groundwater regime and calculation of yield response in North China Plain: a case study of Luancheng County in Hebei Province JIA Jin-sheng, YU Jing-jie, LIU Chang-ming (Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China) 1 Introduction The North China Plain (referring to the vast plain area north to the Yellow River, against Taihang Mountains in the west and facing Bohai Sea in the east) is the political, economic and cultural centre of China. The total industrial output value amounted to one-fifth of the country´s total and the total grain output, one-seventh in 1987 (Liu et al., 1996). The North China Plain, as a region with rapid economic growth in the first ten years of the 21st century, has insubstitutional functions in the aspects of national food security, energy, raw material, urbanization and so on. However, the water resources per capita available in the North China Plain is only 450 m3. Water has been one of the most important factors restricting the economic development of the region. Large scale groundwater exploitation was carried out in the 1960s. The number of motor-pumped wells increased from 1,800 in the 1960s to 700,000 in 1997. At the same time, the annual amount of shallow groundwater exploited went up from 3,885 km3 in the 1960s to 7,913 km3 in the 1970s. And the average annual shallow groundwater exploitation amount between 1985 and 1997 was up to 10,579 km3, which caused the groundwater table decline in the North China Plain. The analysis of 600 shallow groundwater observation wells revealed the average buried depth of groundwater decreased from 7.23 m in 1983 to 11.52 m in 1993. The annual average decline rate was 0.43 m/yr (Liu et al., 2001). Researches have been conducted on groundwater early in the North China Plain. Hydrogeological investigations began in the 1950s. Preliminary groundwater resources evaluation of the whole region was completed in the 1960s (Zhang et al., 2000). The National Key Project-Water Resources Evaluation and Development in the North China Plain in the Sixth Five-Year Plan period had done much analysis and experimental work on the hydrogeological parameters from the point of hydrogeology and hydrology. The calculation precision and fundamental theory was greatly improved than the previous work (GHSHP, 1990). The 57th item-the National Key Project on Groundwater Resources Evaluation in the North China Plain had made thorough analyses and calculations on groundwater recharge by precipitation, availability of groundwater resources and the available exploitation amount in the mountainous and hilly areas. The availability of groundwater resources, total recharge and the available exploitation amount were calculated separately in different zones according to hydro geological units, water resources sub-areas and administrative divisions (GHSHP, 1990). Both of the projects are focu sed on the macroscopic scale for the purpose of providing basis for decision making and national macro economic devel opment planning. Agricultural natural resources investigation and agriculture zonation reports on Luancheng County we re the earlier research references on water resources. The investigation team of agricultural resources composed of t he Chinese Academy of Sciences and Luancheng County accomplished the report (CAS et al., 1979). The main work in thi s report was the compilation of the actual investigation data. There was no improvement on calculation theory, metho d and approach. The latest water resources evaluation by Water Conservancy of Luancheng County was in 1993 (LCWRMO, 1 993). It gave an investigation, analysis and calculation on the current water consumption and water-used structure fo r the future, in which the current availability of groundwater resources data were cited from the Hebei Province grou ndwater resources evaluation report. Modflow is an authoritative software for groundwater numerical simulation at th e present time. Up to now, there has been no real application examples in the North China Plain. Wu Jianfeng (Wu et a l., 2002), Wu Qiang (Wu et al., 1999) and Wei Linhong (Wei et al., 2000) discussed the principle, function and applic ation prospect of Modflow in their papers without discussion on the actual applications. He Shan (1999) calculated th e contamination of one presumption river in the Haihe Basin using Processing Modflow. But it was only an ideal exampl e. In this paper, a groundwater flow model was developed based on the actual hydrogeological condition and simulated groundwater flow using Visual Modflow 2.8.1 version. On the basis of the simulation, the groundwater resources in Lua ncheng County were evaluated. This work is a successful application of Modflow in China. The simulation result is use ful for guiding the rational water consumption and controlling the groundwater table decline. 2 Factors affecting gro undwater table Located in the southwest of Hebei Province, Luancheng County is a part of the North China Plain. It i s part of the alluvial and diluvial fans of the Hutuo and Huaisha rivers. Terrains decline gently from northwest to s outheast. The elevation of land surface ranges between 45 m and 66 m. And the land surface gradient ranges from 1/50 0 to 1/1000. Luancheng County lies in the warm temperate and semi-humid zone. Affected by the continental monsoon cli mate, it has an obvious seasonal changes. It is dry and windy in spring, hot and rainy in summer, mild cool and shin y in autumn, and cold with less snow and precipitation in winter. The mean annual temperature in Luancheng County is 12.2 oC, the accumulated temperature ≥10 oC is 4,251 oC, the frost-free period is 191 days, the annual sunshine tim e is 2,544 hours, the relative humidity is 65%, the normal annual evaporation is 1,644.5 mm, the annual average wind speed is 2.6 m/s, and the mean annual precipitation is 483.5 mm (1949-2000) (CCCLCHP, 1995; Jia et al., 2002). The ag riculture of Luancheng County is well developed with a long history of well irrigation mainly from groundwater, whic h is one of the most important commercial grain production bases in the North China Plain. The total number of wells rose from 20 in 1953 to 9,558 in 1999. And the grain yield increased from 3.89?104 t in 1952 to 2.76?105 t in 2000 (H BS, 1984-2000; SBS, 2001). However, the groundwater buried depth decreased from 3-4 m in 1949 to 20-30 m in 2000. Wit h groundwater table going down, a great number of wells were obsolescence and pumping machines were replenished, whic h added much heavier economic burdens to the local farmers. Meantime, groundwater table decline led to groundwater co ntamination. This phenomenon was rather obvious along the discharge channel. So how to adopt the effective measures t o prevent the groundwater table decline has become a hot topic attracting many scholars. 2.1 Precipitation The precip itation is the source for both surface water and groundwater. Affected by the geological and hydrogeological conditio ns, the form and distribution of the groundwater has a geophilic feature. But there is close correlation between the groundwater distribution and the regional hydrological cycle. The interannual variabilities and annual allocation of the precipitation affect the changes of the groundwater directly. According to the annual precipitation data, the ave rage decadal precipitation decreased gradually during the 1970s, 1980s and 1990s. The precipitation was 479.5 mm in t he 1970s, 463.7 mm in the 1980s and 401.1 mm in the 1990s. Based on the observation well No.0604 (Figure 1), the grou ndwater table descended from 40.86 m in 1972 to 21.93 m in 2000 with mean annual drawdown of 0.65 m. The groundwater table change has a good relationship with precipitation. As Figure 1 shows, groundwater table rose after pluvial peri ods, such as 1976, 1977, 1982, 1990 and 1996. This indicated a close relationship between rainfall and groundwater ta ble. When precipitation is heavy, there is much recharge of rainfall and river infiltration, while the groundwater wi thdrawal decreases relatively. Both of the functions caused the temporal rise of the groundwater table. Figure 1 Rela tionship between groundwater table and precipitation in Luancheng County Figure 2 Relationship between groundwater ta ble and grain output in Luancheng County (1974-2000) Figure 3 Variation of the crop cultivating structure in Luanchen g County (1949-1999) 2.2 Water consumption for grain production and crop planting structure 2.2.1 Grain yield The for mation of the grain yield is the result of the photosynthesis and transpiration. Generally speaking, the crop output is directly proportional to the crop water demand. That is to say, the higher the crop output, the more the water demand. When the rainfall is not enough for the crop growth, irrigation would become an important way to ensure a high and steady grain output. In the study area, to sustain high and steady crop yield is at the expense of over-exploitation of groundwater. The relationship between grain output and groundwater table during the period 1974 to 2000 can be described as a "X-shaped" curve (Figure 2). The grain output was 1.5?105 t in 1974, 3.18?105 t in 1999 and 2.76?105 t in 2000 (HBS, 1984-2000; SBS, 2001). Yet the groundwater table dropped from 43.6 m in 1974 to 29.1 m in 2000. As groundwater table declined, unsaturated zone became thick, which resulted in relatively little recharge to groundwater. So this is also an important reason for the groundwater table´s continual decline. Of course, the increase of the grain output is related with the improvement of the cropping and agronomic measures such as racial amelioration, application of fertilization and so on. But the critical factor to sustain high grain yield in this area is irrigation. 2.2.2 Crop planting structure In Luancheng County, the main crops are winter wheat and summer maize with a total water demand of 1,000 mm. But the normal mean annual rainfall in Luancheng County is only 480 mm, and about 80% happens from July to September. The temporal distribution of rainfall is not suitable to the critical period of crop water demand. In order to get high yield, irrigation becomes necessary to supply enough water for crop consumption. As a case study of winter wheat, the normal mean rainfall during winter wheat growing season is about 150 mm, yet the total water demand for winter wheat is 500 mm or so. There is less than 100 mm of rainfall in March, April and May. And this period is very important for winter wheat growth. A great amount of water is used for crop output. As a result, farmers have to pump groundwater to irrigate the winter wheat. This kind of intensive exploitation for agriculture destroyed the law of natural circle law of groundwater flow seriously. This caused groundwater table´s continual decline. The planting area of much water consumed crops such as winter wheat and summer maize has increased fast and sharply since 1967. The area of other crops such as cotton, millet, oil-bearing crops and potatos decreased gradually (Figure 3) (HBS, 1984-2000; SBS, 2001). The great adjustment of the crop planting structure added a heavy burden to the local groundwater resources. At the same time, with the increase of the upper aeration zone and water consumption for crop growth, the recharge of irrigation and rainfall to groundwater becomes less and less. This kind of unbalanced exploitation and replenishment caused the decline of the groundwater table. 2.2.3 Upstream hydraulic engineering Before 1980, four seasonal rivers -- Xiaohe River, Yehe River, Shahe River and Nihe River flowed through Luancheng County. The normal mean annual runoff of these four rivers totaled 0.454 billion m3. By the end of 1978, 31 reservoirs with a capacity of above 10 million m3 had been constructed, and the total reservoir capacity reached approximately 1.1 billion m3 (CAS et al., 1979). This caused no water discharge from these rivers in both dry and rainy years. Since then, rivers in the County have dried up in either dry or rainy years. The reduction of the river flow aggravated the decline of groundwater table to some degree. 3 The groundwater simulation model of Luancheng County 3.1 Hydrogeological condition Luancheng County belongs to the hydrogeological unit of Taihang Mountain pediment. The Quaternary system gets thicker gradually from northwest to southeast. According to the deposition sequence and rock properties, it can be divided into two sub-zones-Hutuo River alluvial and diluvial fans and Huaisha River alluvial fan. 3.1.1 Hutuo River alluvial and diluvial fan sub zone This zone is distributed in the northern, central and southeastern parts of Luancheng County. According to the rock properties it can be divided into four water-bearing stratums. The first water-bearing stratum (Q4): the buried depth of floor is 12-20 m. There are 0-2 layers usually in the water-bearing stratum, and the depth of each layer is 2-5 m. The grain is fine sand and medium fine sand. This stratum belongs to interstitial water. But its amount is very little. So it could not be used for well construction. The second water-bearing stratum (Q3): the buried depth of floor is 60-120 m. There are 3-7 layers usually in the water-bearing stratum, and the depth of each layer is 5-15 m in the north and thinner in the south. The grain becomes thinner from north to south. There is close hydraulic relationship between Q4 and Q3. These two layers belong to lightly confined water-bearing stratum and the current main exploitation sector. The well discharge is 50-70 m3/h*m in the north, 30-50 m3/h*m in the central part and less than 30 m3/h*m in the south. The third water-bearing stratum (Q2): the buried depth of floor is 160-230 m. There are 5-10 layers usually in the water-bearing stratum, and each layer is 3-7 m deep. The well discharge is 14.7 m3/h*m. The rock property of the water-bearing stratum is mainly medium sand, medium-fine sand with gravels in some areas in the upper part. And in the lower part, the rock property is coarse sand, coarse-medium sand with gravels. There has a stable watertight layer of 10-30 m deep composed by loam and mild sandy soil at the top of this aquifer. This water-bearing stratum belongs to confined water. The fourth water-bearing stratum (Q1): the aquifer changes very much. The buried depth of floor is 308-421 m. There are 0-10 layers usually in the water-bearing stratum, and each layer is 5-15 m deep (CCCLCHP, 1995; LCWRMO, 1993). 3.1.2 Huaisha River alluvial fan sub-zone This zone lies in the southwest of Luancheng County. The buried depth of aquifer top is 40-80 m. The aquifer thickness is 22-24 m. Th e rock property is mainly composed of coarse and medium coarse sand and gravels. The well discharge is less than 30 m 3/hm. The degree of mineralization is less than 0.5 g/l (CCCLCHP, 1995; LCWRMO, 1993). The aquifer of the two sub zon es is overlapped at the joint part. So they can be considered as an entity aquifer. At the present time, the main exp loitation aquifers are the first and second, which belong to mixed exploitation. So the model mainly simulates the gr oundwater flow of main exploitation parts in Luancheng County. 3.2 Hydrogeological concept model 3.2.1 General analys is of the groundwater system Through the analysis of the hydrogeological conditions and the utilization of local grou ndwater resources, it is considered that the groundwater system of Luancheng County belongs to this type-recharge of rainfall and irrigation infiltration and agricultural exploitation. The research field forms a comprehensive system, which is composed of groundwater recharge, runoff and discharge. There are two main recharge sources. The first is la teral recharge in the northwest. The second is vertical recharge, including rainfall infiltration, irrigation regress ion and river leakage. The discharge of the groundwater is mainly agricultural exploitation. The lateral outflow in t he southeast is very little. Because the buried depth of the groundwater is very great, the shallow groundwater evapo ration is near to zero. The groundwater flows from northwest to southeast. The hydraulic grade is homogeneous with th e landform slope. However, under the natural condition before groundwater exploitation on a large scale, the recharge s are mainly river leakage, rainfall infiltration, lateral flow and irrigation regression (surface water irrigatio n), and the discharge is mainly lateral outflow and shallow groundwater evaporation. 3.2.2 Hydrogeological condition generalization The southern and northern boundaries of calculating area is orthogonal similarly with the groundwater table contour. They can be regarded as no flow boundary because water exchange is quite small. The northwest boundar y can be considered as flow boundary because the inflow data is adequate and a more reliable recharge amount can acqu ire. The southeast boundary is parallel with groundwater table contour, the hydraulic grade changes slightly, and we consider it as head-dependent boundary (Tang et al., 1998; Thomas E Reilly, 2001). The bottom boundary of the researc h area is a relatively aquitard layer with clay. It can be considered as aquitard boundary. The rock property of aera tion zone is sand and medium-fine sand. The aquifer can get recharge of rainfall, irrigation and river leakage. The g roundwater storage is in the loose stratum of the Quaternary system. The aquifer has the characters of heterogeneity and anisotropy. The groundwater table has been declining year by year. So the groundwater flow is not steady. We loo k it as three-dimension flow. 3.3 Numeric simulation model Based on the hydrogeological conditions of the research fi eld, we can describe the groundwater flow as following mathematic model (Tang et al., 1998; McDonald M C, 1998): wher e h is the potentiometric head (m), B is the bottom elevation of the aquifer (m), q (x, y, z, t) is unit discharge cr ossing through the boundary (m2/T), W is a volumetric flux per unit volume and represents sources and/or sinks of wat er (m3), h0 (x, y, z) is initial head (m), Kx, Ky and Kz are values of hydraulic conductivity along the x, y, and z c oordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (m/d), Sy is the specifi c yield, (1 is discharge calculation boundary, n is inner normal line, t is time (d). Figure 4 Discretization mesh o f research zone in Luancheng County Figure 5 Zonation map of hydrogeological parameters in Luancheng County Figure 6 Fitting curve of the calculating data and observation data in Luancheng County Table 1 Partition table of hydrogeolog ic parameters of the aquifer 3.3.1 Model solution Visual Modflow 2.8.1 version developed by Waterloo Hydrogeologic In c. was used to solve the model. Visual Modflow is based on the Modular Three-dimensional Finite-difference Groundwate r Flow Model, integrated with Modflow, Modpath, MT3D and PEST greatly. It is one of authority professional softwares at present (WHI, 1999 and 2000). We combined the first and second aquifer into one layer. During the simulation proce ss, we divided the whole research field into 900 cells with 30 rows and 30 columns (Figure 4). There are 390 ineffect ive cells, 510 effective cells and 26 discharge cells among the 900 cells. In this calculation, we run the well stres s subprogram. All of the recharge and discharge are described as injection well and pumping well. River runoff, farml and irrigation time and amount were set by on-the-spot investigations and using observation data. And the schedule o f the injection and pumping wells were determined. We used the WHI subprogram recommended by the Waterloo Hydrogeolog ic Inc. to solve the model. The simulation time is one year with 12 stress periods. The time step is 10 days. 3.3.2 M odel calibration The water head at the site of the observation well was calculated using the model, and compared wit h the observation data. The hydrogeological parameters were acquired by inverse computation based on five observatio n wells selected in this simulation process. These wells lie in the first and second aquifers. The calibration time b egan on January 1, 1990 and ended on December 31, 1990. There is a 12-time period and the time step is 30 days. The s imulation results are listed in Table 1 and Figure 5. Information of the five wells can be seen in Table 2 and Figur e 6 which show that the maximum mean error of these wells is 0.14 m. The negative and positive errors are rather prop ortionate. The system performs steadily. This indicated that the generalization of the hydrogeological conditions, de termination of the boundary conditions and the mathematic models are fine for the practical research field. The resul ts would be reliable using this model to calculate and predict. Table 2 Statistical parameters of the calculation data and observation data 4 Response of groundwater regime to yield capacity calculation Based on the water balance principle, the influence of different yielding capacities on groundwater resources was analyzed by using the calibrated model. The yield for agriculture in 1990 was 1.01?108 m3. It was considered as current level. Then the groundwater tables at five observations were calculated by the model under different groundwater withdrawal-a reduce by 0.14?108 m3 (50 mm) and 0.29?108 m3 (100 mm) and an increase by 0.29?108 m3 (100 mm) compared with the current. The simulated results were listed in Table 3. It can be seen that the groundwater table rises by 0.25 m and 0.56 m in June under the condition of reducing the exploitation amount by 50 mm and 100 mm respectively. And in December the values are 0.33 m and 0.64 m. But the rise of groundwater table was not linearly related with the reduction of the exploitation. When reduced by 50 mm, the groundwater table rose by 0.25 m in June and 0.33 m in December compared with the current groundwater table. And when reduced by 100 mm, the groundwater table rose by 0.31 m in June and December compared with the current groundwater table. However, when the exploitation increased by 100 mm, the groundwater table declined by 0.65 m and 0.45 m in June and December respectively. The groundwater table change was closely related to the amount and time distribution of precipitation, groundwater exploitation and discharge amount of the upstream rivers in Luancheng County. The groundwater exploitation for agriculture was the important factor influencing groundwater table change known from the above analysis. Recharge and discharge mutually influenced groundwater table range. And there is an inexorable relation between groundwater exploitation, rainfall and discharge of the upstream rivers. So we use the rise ratio to express the influence of different amount of exploitation on the groundwater table. The rise ratio here is defined as the ratio of groundwater table rise and amount of groundwater exploitation. By calculation, the groundwater table rises 0.33 m and 0.31 m respectively on account of reducing withdrawal of 50 mm and 100 mm. It decreased as withdrawal decreased. A conclusion could be drawn that external water resources needed to recharge the groundwater for preventing the groundwater table decline in the study area. This also gave a demonstration for the necessity of south-to-north water transfer. Table 3 Groundwater table at different withdrawal in Luancheng County 5 Conclusions The influencing factors on groundwater and the groundwater response to different withdrawal in Luancheng County were simulated by using Visual Modflow software. The results can be summarized as: (1) Water resources shortage would be the key factor restricting the economic development of the North China Plain. Under the condition of no continual heavy rainy year and a certain external water supply, the groundwater resources of the North China Plain would be faced with depletion. The water supply situation would become more and more serious. (2) The rainfall, agricultural output, crop planting structure and regional water distribution had a close relationship with the groundwater dynamic shift. Particularly, water saving for agriculture is very important for groundwater resources´ sustainable utilization. (3) On the piedmont with integrity aquifer, the first and second aquifers could be looked as one unite layer. The hydraulic conductivity and specific yield could be calculated by weight according to the rock property and aquifer thickness. (4) Raising irrigation efficient and using rainfall fully were the important ways to prevent the groundwater table decline. References

关键词： groundwater table; Visual Modflow; zonation of the hydrogeological parameters; groundwater simulation model; groundwater exploitation

