ground water

Case Study/

Ground Water Sustainability: Methodology and Application to the North China Plain

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Abstract

This article analyzes part of a ground water flow system in the North China Plain (NCP) subject to severe overexploitation and rapid depletion. A transient ground water flow model was constructed and calibrated to quantify the changes in the flow system since the predevelopment 1950s. The flow model was then used in conjunction with an optimization code to determine optimal pumping schemes that improve ground water management practices. Finally, two management scenarios, namely, urbanization and the South-to-North Water Transfer Project, were evaluated for their potential impacts on the ground water resources in the study area. Although this study focuses on the NCP, it illustrates a general modeling framework for analyzing the sustainability, or the lack thereof, of ground water flow systems driven by similar hydrogeologic and economic conditions. The numerical simulation is capable of quantifying the various components of the overall flow budget and evaluating the impacts of different management scenarios. The optimization modeling allows the determination of the maximum "sustainable pumping" that satisfies a series of prescribed constraints. It can also be used to minimize the economic costs associated with ground water development and management. Furthermore, since the NCP is one of the most water scarce and economically active regions in the world, the conclusions and insights from this study are of general interest and international significance.

Some figures in this paper are available in color in the online version of the paper.

Introduction

North China Plain (NCP) is a common name for the plain areas of three major river basins in northern China, namely, the Huang (Yellow), Huai, and Hai river basins. It covers an area of 320,000 km^2 with a population of more than 200 million and is the largest alluvial plain of eastern Asia (Kendy et al. 2003b). From the viewpoint of water resource management and economic importance, a narrower definition of the NCP is more commonly used—the region bordered on the north by the Yan Mountain, on the west by the Taihang Mountain, to the south by Yellow River, and to the northeast by Bohai Gulf (Figure 1). This region includes all the plains of Hebei Province, Beijing and Tianjin, and the northern parts of the plains in Shandong and Henan Provinces. It was in the NCP that the ancient Chinese civilization originated as a society developed from agriculture and has since flourished for more than 4000 years (Postel 1999). Today, the NCP remains the most important economic and political center of China.

The environmental conditions in the NCP, however, do not justify the high concentration of population and economic activities in this region. On average, the local climate produces about 500 mm of precipitation annually, which accounts for only 335 m^3 of renewable water resources per capita per year (China Geological Survey 2005). This is only one-third the threshold value of 1000 m^3 per capita adopted in the widely used Falkenmark indicator or "water stress index" (Falkenmark et al. 1989), denoting a region experiencing water scarcity. In addition, precipitation fluctuates widely from one year to the next, with 50% to 80% of the total precipitation being concentrated in the summer monsoon months (July

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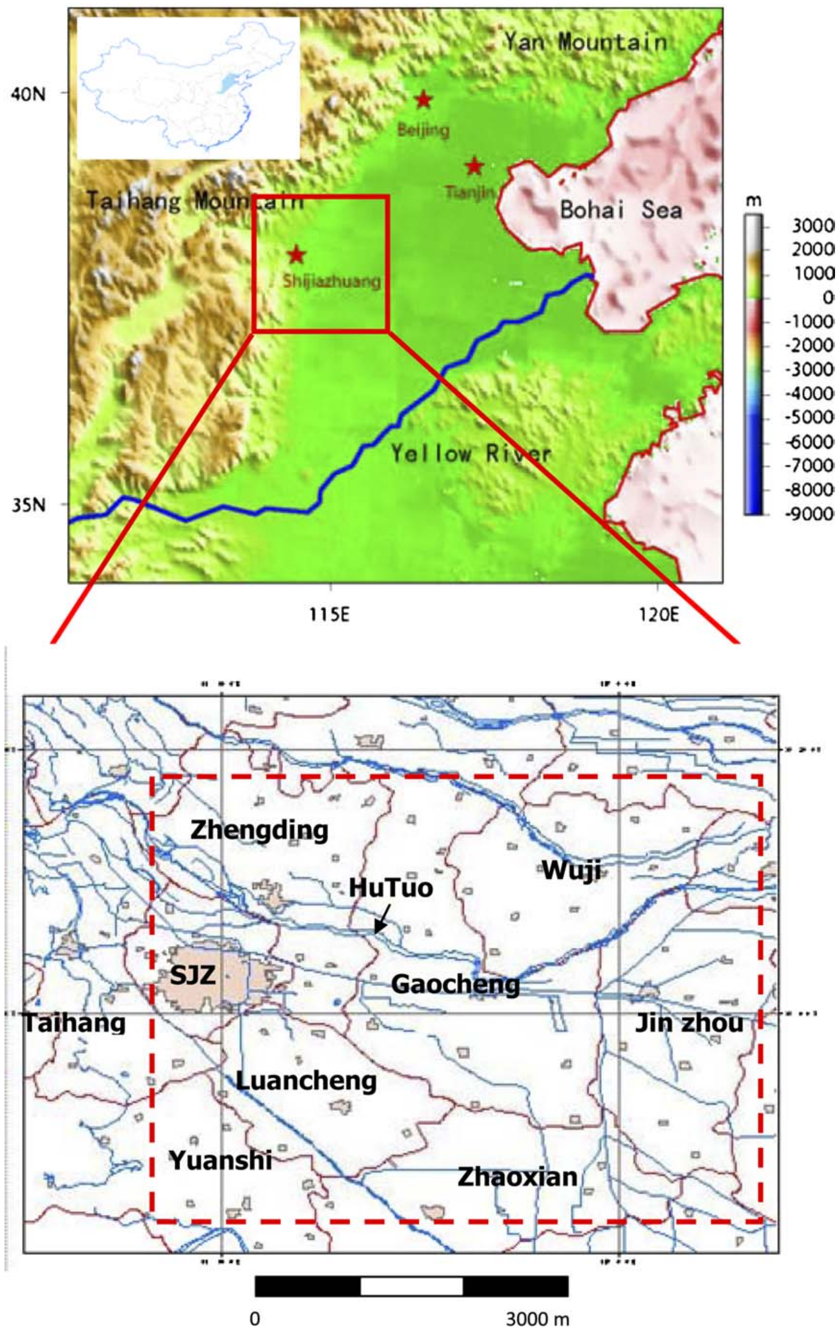

Figure 1. Location of the NCP and the study site.

to September). The consequences of such a climate are frequent flooding and drought events. For example, there have been 135 floods and 140 droughts over the past 500 years (Huai River Commission 1998). Geopolitical factors, however, dictated the necessity of maintaining a strong agriculture settlement and military presence in the NCP to ward off incursions by the northern nomadic tribes and to safeguard the middle kingdom establishment. Therefore, throughout thousands of years, both money and human labor have been invested in the construction and maintenance of countless hydraulic works in the NCP to fight the floods and droughts and to keep grain and goods flowing (via canals and rivers) from south to north (Elvin 2004).

In comparison, the development of ground water resources in the NCP for urban and industrial growth and for agricultural irrigation is a relatively new story, yet still driven by similar environmental and human pressures. The 1950s first witnessed the arrival of mechanized pumping wells in the NCP. The severe drought in 1965 led to the first big wave of well construction. During that year alone, more than 300,000 wells were drilled. Since then, the number of wells in the NCP has increased rapidly, and today there are more than 1.2 million wells. This has been accompanied by a significant increase in agricultural production and rapid decline of ground water levels. In many parts of the NCP, the ground water levels are now declining at a rate of more than 1 m/year. The NCP aquifer system has quickly become one of the most overexploited in the world (Ministry of Water Resources of PRC et al. 2001; Kendy et al. 2003b). Illustrated in Figure 2 is a typical example of the water level decline in

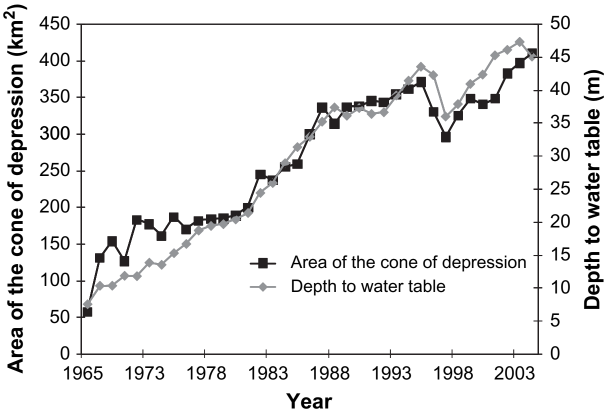

Figure 2. Changes in the area of the cone of depression and the depth to water table in SJZ City.

the Shijiazhuang (SJZ) area over the past 40 years. Also shown in Figure 2 is the change in the total area of the cone of depression resulting from ground water overdraft.

The purpose of this article is to analyze part of a ground water flow system in the NCP to explore the implications for sustainable development and management of ground water resources. A transient ground water flow model was first constructed and calibrated to quantify the changes in the flow system since the predevelopment 1950s. The flow model was then used in conjunction with an optimization code to determine optimal pumping schemes that improve ground water management practices. Finally, two management scenarios were evaluated for their potential impacts on the ground water resources in the study area.

Although this study focuses on the NCP, it is of general interest and international significance. First, it illustrates a general modeling framework for analyzing the sustainability, or the lack thereof, of ground water flow systems driven by similar hydrogeologic and economic conditions experienced in the NCP. Second, the NCP is the most important political and economic center of China. It is also one of the most depleted aquifer systems in the world. Ground water overexploitation and ground water–induced environmental problems in the NCP have drawn attention from researchers and organizations around the world. The major water user in the NCP is the intensive irrigation-based agriculture, which is a setting ideal for analyzing the effects of human activities on aquifers. The NCP is also the location for a mega water transfer project—the South-to-North Water Transfer (SNWT) project. The confluence of these factors makes NCP an interesting and instructive case study of international significance.

Study Site and Hydrogeologic Setting

The study site is the metropolitan SJZ City and its surrounding seven rural counties. It is located in the piedmont plain of the Taihang Mountain, the western boundary of the NCP, and situated at the center of the alluvial fan of the Hutuo River. The location and boundaries of the study area are illustrated in Figure 1. The study site covers an area of 4000 km^2 with a total population of nearly 5 million and is representative of many areas in the NCP where favorable hydrogeologic conditions have allowed intensive ground water exploitation. The average monthly temperature in this region ranges from about −4 °C in January to 25 °C in July. Average annual rainfall is about 500 mm, with most of it occurring during summer, very little during spring and autumn, and even less in the dry, cold winter (Liu et al. 2001).

Ground water in the study area occurs in aquifers of porous Quaternary alluvial deposits, which are composed of laterally discontinuous layers of gravel, sand, and clay (Figure 3). The deposits can be divided into a shallow unit and a deep unit. The shallow unit, extending to a depth of about 40 to 60 m below the land surface, is composed of sand and gravel. This unit has good permeability and is quite water productive. The deep unit has variable thickness, the bottom of which is at 300 to 370 m

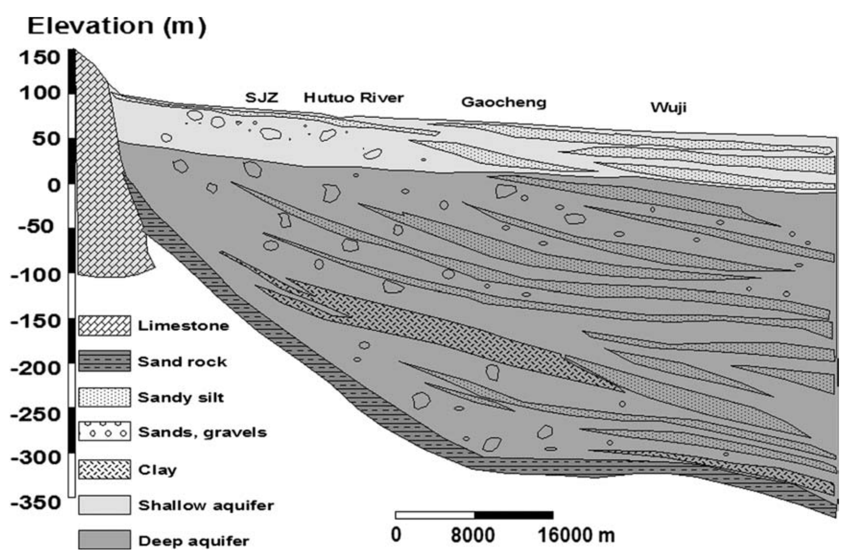

Figure 3. Hydrogeologic cross section (west to east) of the study area (HEGS 1992).

below the sea level, and is mainly composed of clay and sandy silt. Generally speaking, the permeability of the deep unit is low and variable. The shallow unit is hydraulically connected with the deep unit. Because the shallow aquifer unit is well developed and is almost depleted, pumping wells have been extracting ground water from the deep unit. Consequently, these two units were considered as a single unconfined aquifer flow system in this study (Chen 1999).

The main sources of ground water recharge in the study area are precipitation, lateral flow from the mountain front, and return flow from irrigation. Infiltration from precipitation is the most important source of ground water recharge because the vadose zone is composed mainly of sand, which has an infiltration factor of about 0.3 (Institute of Hydrogeology and Environmental Geology [IHEG] 1988). The lateral flow from the front of the Taihang Mountain along the western border provides another source of recharge. Because flooding is the main irrigation mode in most of the study area, the return flow from irrigation is a source of recharge.

Within SJZ City, the primary water uses are for households and industry. For the other seven surrounding counties, grain production uses most of the water. Ground water provides the majority of the water used for irrigation in the study area. The water table is currently more than 10 m below ground surface; thus, evaporation of ground water has become negligible (Jia 2002). Enlargement of the cone of depression in the vicinity of SJZ City caused an obvious ground water divide to the east of the city, which led to a reversal in water flow direction and greatly reduced ground water flow to the lower reaches. Currently, ground water discharge in the study area is mainly through intensive localized pumping in SJZ City and widespread pumping via small capacity wells for irrigation in the surrounding counties.

The previous discussion shows that the dynamics of the ground water flow system in the study area is mainly controlled by precipitation and pumping. Basically, the regional ground water flow direction is from the northwest to the southeast, except in the vicinity of SJZ City where ground water converges toward the center of a large cone of depression due to intensive localized pumping. The hydraulic gradient is consistent with the topography, steep in the northwest, and gentle in the east.

Flow Model Development and Calibration

Conceptual and Mathematical Models

The purpose of developing the ground water flow model was to quantify the current water budget and to assess the future sustainability of ground water resources in the SJZ region under various water management scenarios. Before the 1960s, large-scale and intensive pumping activities had not started, and ground water in the study area flowed mostly under natural conditions, subject to little human impact. For this study, the flow field prior to 1960 was considered as being steady state and used as the initial condition for subsequent transient simulations of the flow system in response to dynamic recharge, pumping, and various boundary conditions.

Many previous studies (IHEG 1988, 1990; Lin and Liao 1995; Chen 1999; Jia 2002; Kendy et al. 2003b; Hydrogeology and Engineering Geology Survey of Hebei Province [HEGS] 2004) have shown that a good vertical hydraulic connection exists between the shallow and deep parts of the unconfined aquifer in the study site; therefore, the unconfined aquifer may be conceptualized as a two-dimensional, heterogeneous, and horizontally isotropic flow system. The governing equation for this system can be expressed as follows:

$$\frac{\partial}{\partial x}\left(Kh\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kh\frac{\partial h}{\partial y}\right) + q_s = S\frac{\partial h}{\partial t} \qquad (1)$$

where h is the hydraulic head (L), t is the time (T), K is the horizontal hydraulic conductivity (LT^{-1}), q_s is the volumetric flow rate of fluid sinks/sources per unit area of aquifer ($L^3T^{-1}L^{-2}$), and S is the specific yield (dimensionless). The governing Equation 1, together with the initial and boundary conditions, constitutes the numerical ground water flow simulation model. The computer code MODFLOW developed by the USGS (Harbaugh and McDonald 1996; Harbaugh et al. 2000) was used for solving the flow model, and the pre- and post-processor Ground-water Modeling System developed by Brigham Young University (Engineering Computer Graphics Laboratory 2005) was used for graphical data input and for analysis and presentation of the output data.

Spatial and Temporal Discretization

The spatial discretization of the finite-difference flow model is shown in Figure 4. The grid contains 135 columns and 130 rows, with a constant spacing of 500 m. Vertically, one model layer is used to simulate a

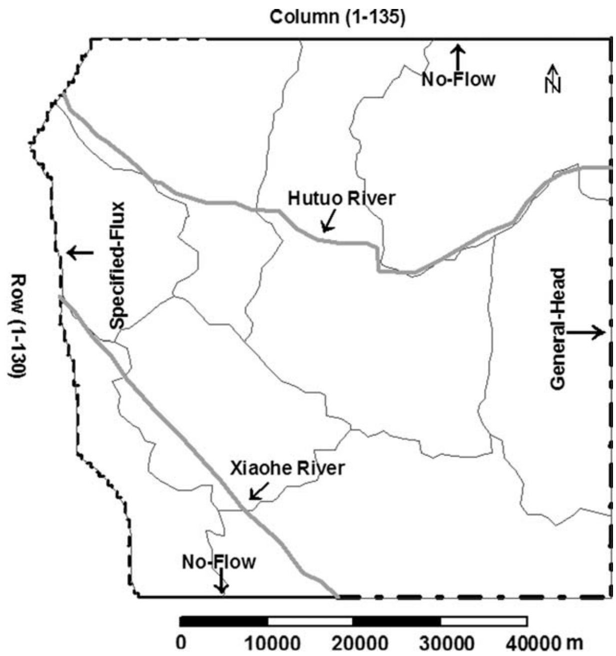

Figure 4. Spatial discretization and boundary conditions of the numerical model.

two-dimensional regional flow system. The top and bottom elevations of the aquifer system were interpolated from the 1:500,000 hydrogeologic map of Hebei Province (HEGS 1992).

For the transient model, the total simulation time of 45 years (1959 to 2004) was discretized into 63 stress periods, each of which contained constant recharge and discharge. In the early years (1959 to 1991), the available pumping data were yearly or even coarser; thus, longer stress periods were used than those after 1991 when more detailed monthly data became available. More specifically, from 1959 to 1991, a total of nine stress periods were used, with one 2-year, five 5-year, two 2-year, and one 1-year stress periods in sequence. From 1991 to 2004, a smaller, constant stress period length of 3 months was used to take advantage of more detailed data.

Boundary Conditions

Within the study area, the physical or hydraulic boundaries were not well defined, so an effort was made to develop a reasonable representation of the boundary conditions. On the western edge of the model lies the interface between the plain and the mountain terrains. The mountain front recharge enters laterally into the study site; thus, the western edge of the model was defined as a specified flux boundary (Figure 4). Along the eastern portion of the southern edge and the entire eastern edge of the model, the regional ground water flow leaves the model domain but may reverse its direction and enter the model domain instead, if excessive pumping occurs within the model domain. This process was represented by imposing general head-dependent boundaries along these model edges. Along the northern edge and the western portion of the southern edge, the regional ground water flow is nearly parallel to the model edges; thus, these edges were treated approximately as no-flow boundaries.

The rate of inflow from the specified flux boundary along the western mountain front was calculated according to Darcy's Law. For transient simulations, the lateral fluxes fluctuated with precipitation. The data (both hydraulic conductivity and hydraulic gradient) from previous studies (HEGS 2004) were used in this study for determination of the specified flux boundary condition. To define the general head boundary condition, two parameters are needed: the boundary head and the conductance between the boundary and the aquifer. The head values at the starting and ending points of the general head boundary were first estimated from the measured water levels in the nearby monitoring wells. The boundary head values elsewhere were then linearly interpolated between the starting and the ending points. The boundary conductance values were dependent on the hydraulic conductivity of the aquifer, and the necessary adjustment was made during the model calibration procedure to achieve the best match between the observed and the calculated ground water levels in the model domain, as described in the subsequent Model Calibration section.

It is noteworthy that the no-flow boundaries and general head-dependent boundaries used in the model are both approximate in nature. However, these boundaries are necessitated by the absence of physical boundaries in the vicinity of the study area. The inaccuracy introduced by the no-flow boundary would likely be small because the boundary is approximately parallel to the general flow direction and sufficiently far away from the pumping centers. The general head-dependent boundary was essentially used as a proxy for the specified flux boundary, where the inflow or outflow across the boundary was calibrated so that the heads along and near the boundary match the observed heads from the monitoring wells.

Assignment and Estimation of Aquifer Properties and Stresses

The hydraulic conductivity (K) for the model domain was determined from the lithology and other information provided by previous investigations (IHEG 1988, 1990; Lin and Liao 1995; Jia 2002). The aquifer was divided into a number of zones, as shown in Figure 5a, with the zonal K values ranging from 20 to 180 m/d. The hydraulic conductivity along the Hutuo River is higher than that on the edge of the alluvial fan. The specific yield of the

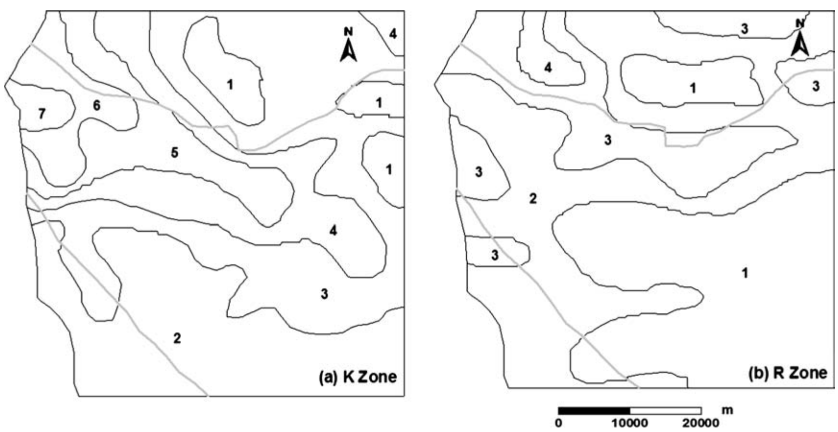

Figure 5. Distribution of parameter zonations: (a) hydraulic conductivity (m/d) (K1 = 20, K2 = 30, K3 = 35, K4 = 50, K5 = 80, K6 = 120, and K7 = 180) and (b) precipitation infiltration factor (IF1 = 0.1 to 0.3, IF2 = 0.3 to 0.35, IF3 = 0.35 to 0.4, and IF4 = 0.4 to 0.5).

unconfined aquifer was set equal to 0.1 based on the available data.

Net recharge to the water table is a driving force for the flow dynamics of the study area. It is a function of precipitation, infiltration, and evapotranspiration (ET). The estimation and assignment of net recharge rates were based on the zones shown in Figure 5b. A combination of previously published data (IHEG 1988, 1990) and model calibration was used to determine the final recharge rates. Kendy et al. (2003a, 2004) developed and applied a 1D soil-water balance approach to quantify the ground water recharge rate in the NCP. Their studies, based on the soil moisture data from the top 2 m soil profiles at 16 sites, suggested a range of recharge rates from 5 to 105 cm/year. They also showed that the recharge rate is highly variable temporally. The model-calibrated recharge rates in this study are generally consistent with those of Kendy et al. (2003a, 2004), although there is some difference due to the regional nature of this modeling study and the point estimates from Kendy et al. (2003a, 2004).

The primary discharge in the study area is pumping for domestic and industrial uses in SJZ City and pumping for irrigation in the surrounding counties. Individual point wells were used to represent the concentrated pumping in SJZ City, while an areal discharge function was used to represent the scattered irrigation withdrawal per unit area. The pumping data were collected from several published sources, including Hebei Water Bureau. Most waste water was discharged to the rural areas outside of the city. Therefore, in the model, no return flow from irrigation or waste water was considered for SJZ City. In the surrounding counties, it was assumed that 15% of irrigation water returned to the aquifer as recharge (Jia 2002).

Model Calibration

The calibration of the numerical model involved two sequential steps. First, the steady-state model representing the predeveloped aquifer system was calibrated to the known flow field prior to 1959. The solution of the steady-state model provided the initial condition for the transient model of the flow field from 1960 to 2004. The transient model was calibrated against the measured water levels available from 1988 to 2003 at 42 observation wells scattered over the model domain (Figure 6a).

Prior to 1959, the water levels in the study area were reported anecdotally rather than measured systematically, so accurate and quantitative calibration was not enforced. During this stage of calibration, the hydraulic conductivity distribution and boundary conditions were adjusted to achieve a reasonably close agreement between the calculated and the observed ground water levels with no ground water pumping. Because the only available data for the observed water levels prior to 1959 existed in the form of a contour map (Chen 1999), the calibration of the steady-state model was based on visual comparison of calculated and observed contour maps.

Based on the preliminary hydraulic conductivity distribution and boundary conditions obtained from the steady-state calibration, the flow model was further calibrated under transient conditions from 1960 to 2004. Transient model calibration was accomplished by simulating ground water level changes in the aquifer in response to changes in recharge and pumping. In each stress period for which the observation data were available, the observed and model-calculated ground water levels at a total of 42 observation wells (Figure 6a) were statistically compared. Through this process, model input parameters, that is, hydraulic conductivity, recharge rates, and boundary conditions, were further adjusted based on previous field data (IHEG 1988, 1990; Lin and Liao 1995; Chen 1999; Jia 2002; Kendy et al. 2003a, 2003b; HEGS 2004) to minimize the discrepancy between the observed and the calculated ground water levels. It is noteworthy that when the hydraulic conductivity distribution must be adjusted to match the transient head data, this adjustment started with the steady-state model so that the single hydraulic conductivity field was used throughout the steady-state and transient flow models. In contrast, recharge rates and boundary conditions were variable from one stress period to another to reflect their dynamic nature. After the absolute mean error between the observed and the calculated water levels was below an acceptable threshold for each stress period, the calibration process for the entire simulation was achieved.

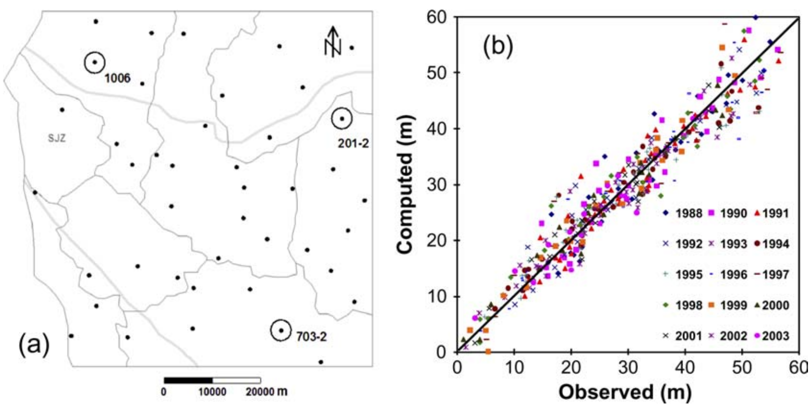

Figure 6. (a) Locations of the observation wells (circled wells 1006, 201-2, and 703-2 are used to show the comparison between the observed and the computed hydrographs in Figure 7 and (b) comparison between the observed and computed heads at all observation wells and times used in transient model calibration.

Figure 6b shows a scatter diagram of the observed vs. calculated heads at all monitoring well locations and observation times. There is fairly good overall agreement between the observed and the calculated values. The comparison of model results with the data from different years and different locations does not reveal any significant bias. Statistically, the mean difference between the observed and the calculated ground water levels for the total of 42 observation wells at all observation times (a total of 414 data points) is 0.09 m. This small mean error suggests that there was no significant global overcalculation or undercalculation in the model results. The final root mean squared error for the 414 data points is 3.5 m, indicating a reasonably robust match between the calculated and the observed heads.

To examine the temporal trend of calculated heads as compared to that of observed heads, three observation wells (well 1006, well 201-2, and well 703-2) as shown in Figure 6a with long time series were selected from different parts of the modeled domain. Figure 7 shows that the calculated and observed hydrographs at the selected observation wells basically have similar trends, with the calculated heads being in good agreement with the observed ones over a long period of time. Based on these model calibration results, the numerical model appears to be a robust simulator of the flow dynamics of the study area and thus may be used as a quantitative tool to analyze the future changes of the ground water resources in the study area.

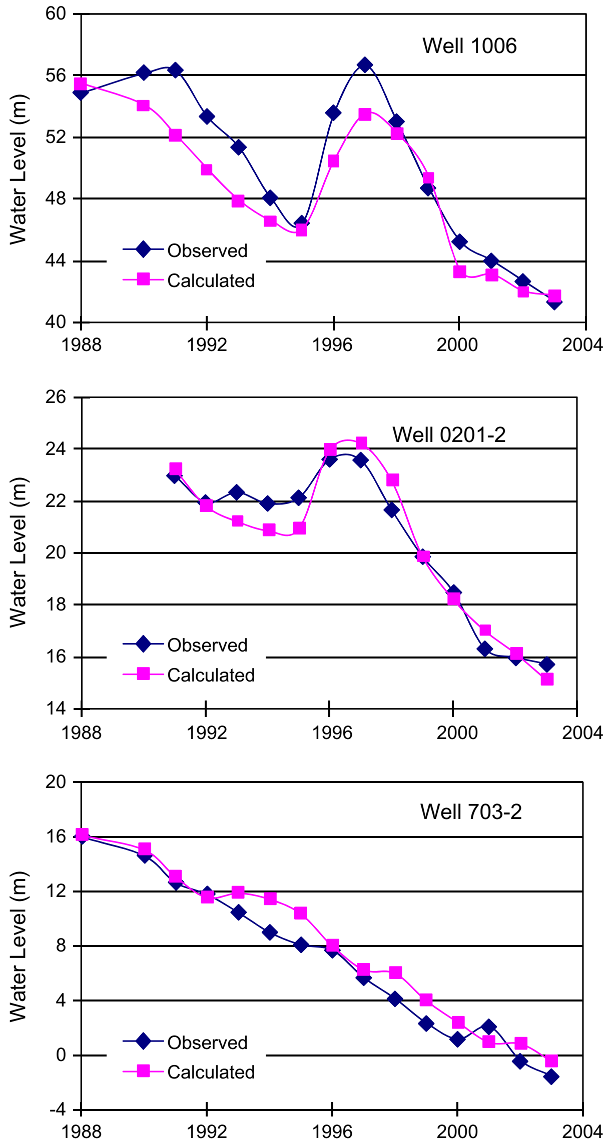

Figure 7. Observed vs. computed hydrographs at three specific observation wells (see Figure 6a for location).

Analysis of Current Conditions

Figure 8a shows the calculated head distribution from the calibrated flow model at the end of the simulation period corresponding to the year 2004, and Figure 8b shows the calculated ground water level decline since the predeveloped condition in 1959. From these simulation results, it can be seen that a large cone of depression has developed in the center of SJZ City. The maximum drawdown at the center of the cone of depression exceeds 50 m. In the neighboring counties, the ground water levels have declined over a range of 26 to 36 m.

For the flow budgets in the study area, major inflow terms were the vertical recharge from precipitation and lateral recharge from the mountain front on the western boundary, and major outflow terms were pumping and lateral discharge across the eastern boundary. Because most rivers (except the rivers for waste water discharge like Xiao He) have gone dry in recent years within the study area, the amount of flow to and from surface water was considered negligible.

Figure 9 shows a breakdown of various inflow and outflow terms for the model domain. It can be seen that ground water recharge resulting from precipitation varied considerably with time. The lateral recharge from the western mountain front remained nearly constant. Pumping was the dominant outflow and it increased steadily from 1959 to 1991 and then fluctuated somewhat from year to year afterward. The outflow leaving the model domain across the eastern boundary decreased as the total pumping increased. In other words, increased pumping led to the capture of the portion of ground water flow that would have left the flow system otherwise. Figure 10 shows a comparison of total inflow vs. total outflow for the model domain. It is apparent that total outflow exceeded total inflow, leading to significant depletion of aquifer storage over time. It is noteworthy that after the 1980s, the aquifer storage was depleted at a faster rate due to increased pumping.

The preceding analysis and discussion of the present conditions in the study area reveal a very dynamic flow system that has evolved significantly since the 1960s in response to pumping activities. The modeling results also clearly indicate that the current utilization of ground water resources in the study area is unsustainable as pumping exceeds recharge by a factor of two, depleting the aquifer at a rapid rate. Either an alternative water supply source must be found or current water use practices must be altered.

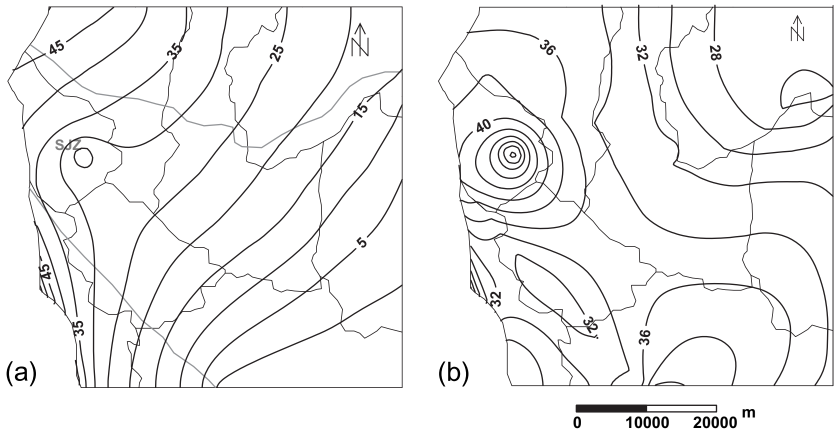

Figure 8. (a) Computed hydraulic head contours for 2004 and (b) ground water level decline from 1959 to 2004.

Development of Optimal Pumping Schemes

From the ground water flow model described previously, it can be seen that the current ground water utilization in the study area is unsustainable. It is urgently needed to optimize the pumping schemes to improve ground water development and management. The history of the ground water development and management in the study area can be traced back to the 1950s. According to "Hebei Water Conservancy Annals" (Hebei Water Conservancy Office 1996), the exploitation of ground water in Hebei Province started in 1950s. In 1958 alone, more than 40,000 wells were constructed throughout Hebei Province. In 1965, severe drought caused intensive construction of irrigation wells. The fastest period for well

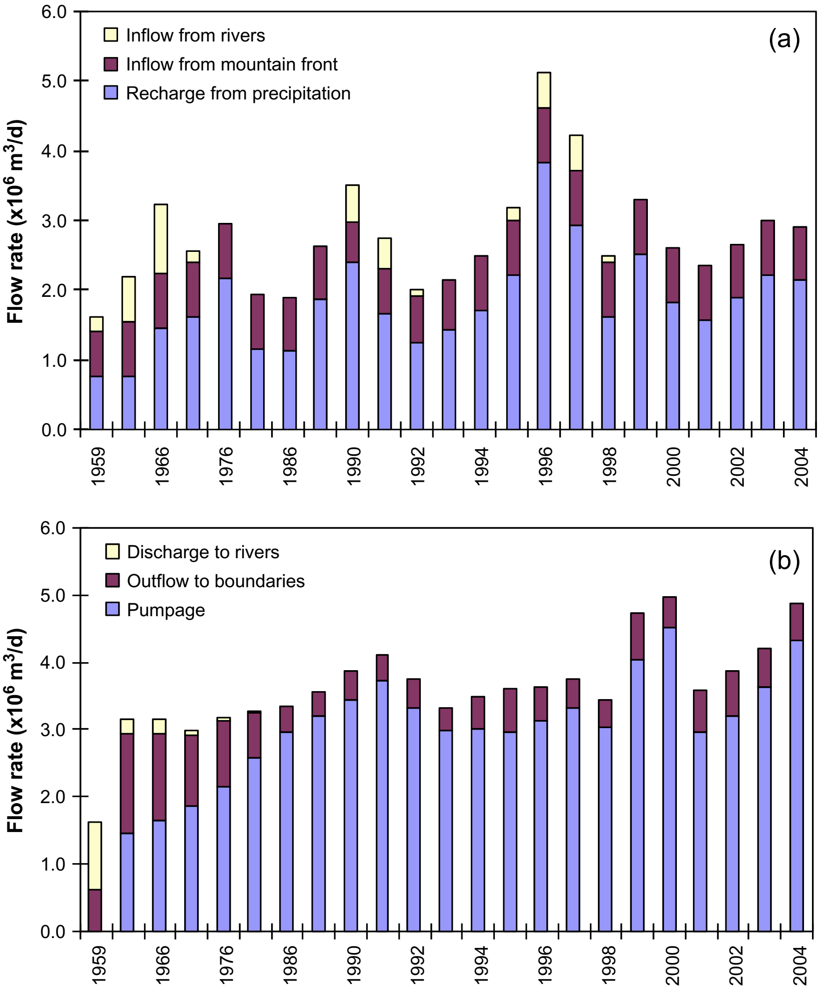

Figure 9. Computed inflow and outflow budgets for the modeled aquifer system.

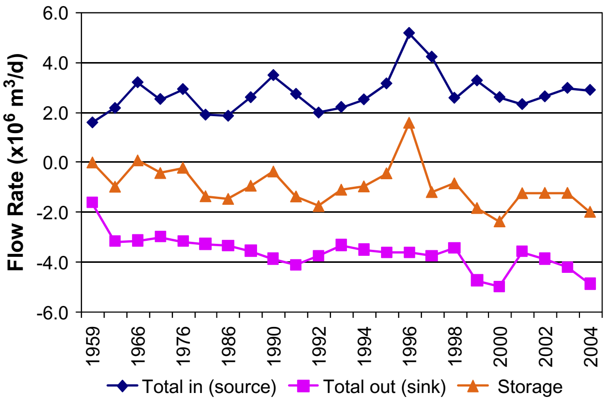

Figure 10. Changes in total inflow, outflow, and storage for the modeled aquifer system.

construction in the region occurred between 1969 and 1979. However, only the number of wells was documented; no good records exist of the quality and the overall pumping rate of ground water.

In the 1980s, the shortage of water resources and the disparity between water supplies and demands became more and more acute. Since the 1990s, more and more attention has been paid to ground water management. A water permit system was implemented in 1993, and many different water-saving technologies have also been implemented. Ground water use in the NCP has evolved from development to management and, subsequently, changed from highly fragmented management to institutionally integrated management (Foster et al. 2004). Although ground water management in the NCP has been greatly improved, there are still many problems. One problem is that there is no link between the estimates of available ground water and the water permits authorized. The water permit system was introduced in 1993, but no quantitative methods exist to accurately estimate the available ground water resources. The water managers have realized the importance of implementing sustainable ground water management, but feasible quantitative methods of optimal or sustainable ground water management have not yet been developed.

Various ground water management models have been constructed in previous studies in the NCP (Jia 2002; Kendy et al. 2003b; Lin and Liao 1995; HEGS 2004; IHEG 1988, 1990). Lin and Liao (1995) set up ground water management models with different decision variables (e.g., ground water pumping rates) and objective functions (such as minimization of ground water drawdown and total pumping costs) for the SJZ region. Linear programming and the simplex method were used for solving the various mathematical formulations. The optimization management models constructed by IHEG (1988, 1990) also coupled a ground water simulation model with a linear management model to search for the maximum economic benefits of ground water use, employing the simplex method. Jia (2002) constructed a multiobjective optimization model to maximize total crop production and total crop benefits under the constraints of irrigation area and irrigation water quantity and used an improved simplex method to solve the management model. However, these optimization methods only work for simple linear problems, while in reality, most of the ground water management problems are nonlinear and complex. Therefore in this study, the Modular Groundwater Optimizer (MGO) (Zheng and Wang 2003) was applied. The MGO code is based on an evolutionary algorithm that was coupled with the MODFLOW code and can be used to solve a variety of optimization problems with highly nonlinear and complex objective functions. It can find global or near-global optimal solutions in the presence of local minima or maxima.

Formulations of the Optimization Model

The key for constructing an optimization model is to formulate an appropriate objective function and to set up proper constraints. In this study, two optimization formulations were constructed. The first formulation is intended to demonstrate the development of optimal pumping strategies, in which the locations of any managed wells do not vary with time over the entire project duration. The objective function for the formulated optimization problem is maximizing the total pumping while maintaining all hydraulic heads above a specified minimum level. The formulation can be expressed as follows:

$$\text{Maximize} \sum_{t=1}^{T} \sum_{i=1}^{nw} (Q_i \times \Delta t)$$

subject to

$$h_i \geq h_{min} \quad i = 1, \ldots, n$$

$$0 \leq Q_i \leq Q_{max}$$

where h_i is the ground water level at the wells, which should be greater or equal to a specified ground water level $h_{\min}$. Q_i is the pumping rate (m^3/d) and is constrained by the lower ($Q_{\min}$) and upper ($Q_{\max}$) limits of the pumping capacity of the wells, *nw* is the number of wells, and *T* represents the management time horizon.

Ideally, determination of $h_{\min}$ should be based on the consideration of the current ground water level at any specific location, the ecological water requirement, and the local hydrogeologic conditions. However, in absence of a more detailed ecological study to better quantify the ecological water requirement, the currently existing water levels were considered as being "ecologically acceptable" and assigned as $h_{\min}$ in this study. In SJZ City where the depth to the water table is already large, $h_{\min}$ was set equal to 100 m below the land surface. For the seven counties around SJZ City, $h_{\min}$ was set at 50 m below the land surface.

The first formulation identifies the maximum yield from the aquifer. In reality, even though the natural conditions allow continuous pumping from the aquifer, the economic factor—high pumping cost—may prevent this. Therefore, the economic factor must also be considered, and the second formulation is to minimize the total pumping cost under the same series of ground water level constraints to satisfy a specified total water demand:

$$\text{Minimize} \sum_{t=1}^{T}\sum_{i=1}^{NW}\left(c \times \text{IW} \times |Q_i| \times (\text{Elev}_i - h_i) \times \Delta t_i\right)$$

subject to

$$Q_{min} \leq Q_i \leq Q_{max}$$

$$\sum_{t=1}^{NW} Q_i \geq Q_{\text{Total}}$$

$$h_i \geq h_{min}$$

where Q_{Total} is the total water demand prescribed for the model domain. The total water demand is usually projected on the basis of population, social, and economic conditions. In this case, however, the present pumping already exceeds the maximum amount that can be extracted from the aquifer. Therefore, the Q_{Total} was taken from the first formulation, that is, the maximum allowed pumping from the aquifer. c is the pumping cost coefficient for lifting a unit volume of water over a unit length. In this study, c is 0.00225 Yuan/m^3/m (Yuan is the Chinese currency unit, also referred to as RMB) in counties and 0.003825 Yuan/m^3/m in SJZ City based on communication with the local water managers. IW is a flag indicator: equal to 1 when the wells are put into service and 0 otherwise. Elev$_i$ represents the elevation of the land surface and h_i is the ground water level at the location i, so (Elev$_i$ – h_i) gives the total lift of ground water for pumping at a certain location i.

It would have been desirable to include more related cost terms in the optimization formulation. However, to estimate those cost terms quantitatively, such as water transfer costs, energy costs, and crop production costs, substantial efforts would be required. Even with those efforts, much uncertainty would still be associated with the cost data. This study was intended only to contrast the difference in pumping costs among different pumping schemes to meet a prescribed total pumping amount and, as such, should be viewed as the first step in cost optimization analysis.

Optimization Results and Analysis

The values of the objective function from the first formulation are shown in Figure 11. After 60 generations (optimization iterations), the optimal objective function value that satisfies all the constraints converged to 2.8 × 10^6 m^3/d as the maximum yield. Compared with the actual pumping rate of 4.1 × 10^6 m^3/d in 2004, the model showed that there was 4.7 × 10^8 m^3 overexploitation of ground water per year.

The difference in ground water pumping rates in the seven counties before and after optimization reveals the rationality of the optimization result. Figure 12 suggests that the pumping in Zhengding (ZD), Yuanshi (YS), and Luancheng (LC) counties should be cut off, the pumping in Gaocheng (GC) and Jinzhou (JZ) counties should be reduced, while the pumping in Wuji (WJ) and Zhaoxian (ZX) counties should be increased. This optimal result seems reasonable because the first three counties are

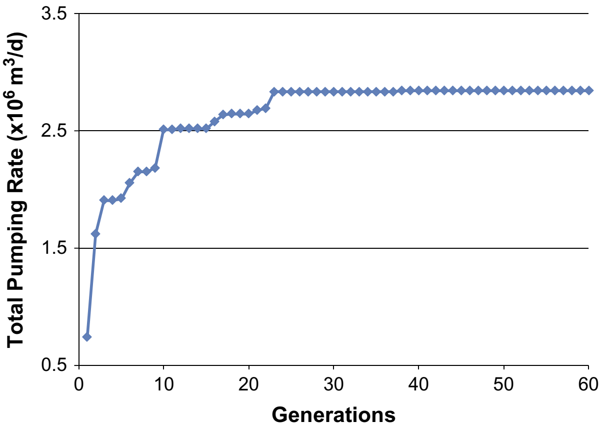

Figure 11. Results of the first formulation, showing the optimization of the total pumping. "Generations" in the horizontal axis represents the number of optimization iterations.

adjacent to SJZ City where the cone of depression exists, while the latter two counties are the most distant. Thus, the elimination of the pumping in the former three counties and an appropriate increase in pumping in the latter two counties would be helpful for controlling the rapid ground water level decline and obtaining the maximum yield.

The optimal objective function value of the second formulation became stable after 70 generations (Figure 13), and the result showed that 13 million Yuan (RMB) per year was the minimal management cost if only pumping cost was considered. Compared with the cost of 32 million RMB before optimization (assuming the pumping locations and rates from the first formulation), the pumping cost was reduced by nearly 19 million RMB per year after optimization.

Figure 14 shows the change in pumping rates before and after the second optimization formulation. To obtain the minimum overall pumping cost, the total pumping in the seven counties should be increased, while that in SJZ City should be reduced. The reduced total pumping rate for SJZ city is 2.2 × 10^5 m^3/d, while the increased total rate for the seven counties is 2.6 × 10^5 m^3/d. This result appears reasonable because the lower ground water level

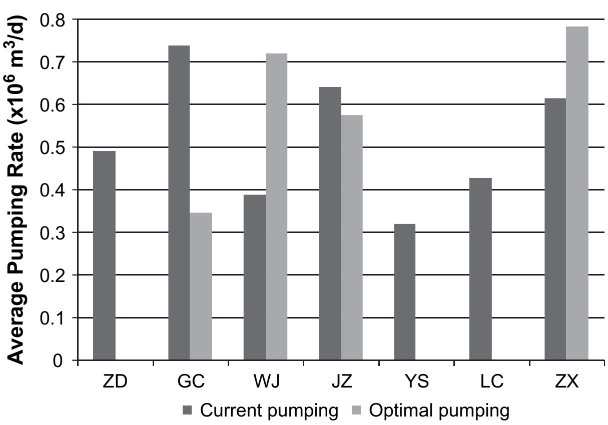

Figure 12. The redistribution of pumping resulting from the first optimization formulation.

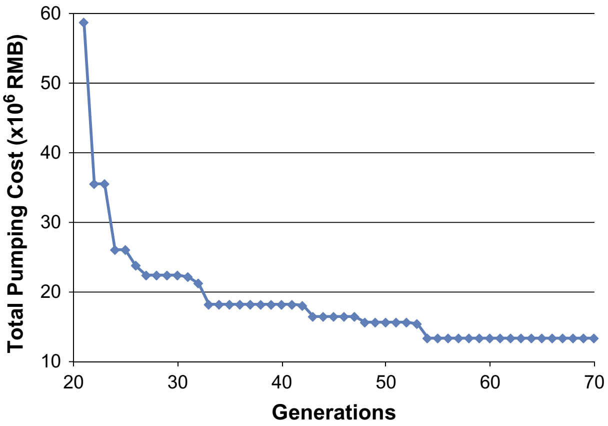

Figure 13. Results of the second formulation, showing the optimization of the total annual pumping costs.

in SJZ City will increase the cost of pumping the same volume of ground water relative to that of the seven counties. Hence, it can be seen that the redistribution of pumping locations can significantly affect the pumping cost. It is noteworthy, however, that this optimization result is based on the consideration of pumping costs only. An implementable management strategy might require the consideration of other socioeconomic factors.

Evaluation of Potential Management Scenarios

The calibrated flow model provides a quantitative tool for examining how potential water resource management scenarios, such as urbanization and the SNWT Project, could impact the ground water conditions in the study area. The findings have implications for the development of improved ground water management practices.

Scenario 1—Urbanization of Rural Areas

China has entered a period of fast growth in urbanization. The economic and political impacts of urbanization have always been recognized, but its hydrological effects have seldom been discussed. Intuitively, urbanization appears to increase the competition for water between different water use sectors, but Kendy et al. (2007) brought up the counterintuitive point that urbanization has a positive role to play in moderating water competition and in reversing ground water declines. Urbanization consumes less water compared with irrigation, and decreasing consumptive water use is the only means to stabilize declining water levels. In this case, the numerical model was used to test the effect of urbanization on the ground water resource in the NCP by assuming that Luancheng County has been urbanized and consumes less water compared with its original use of water for irrigation.

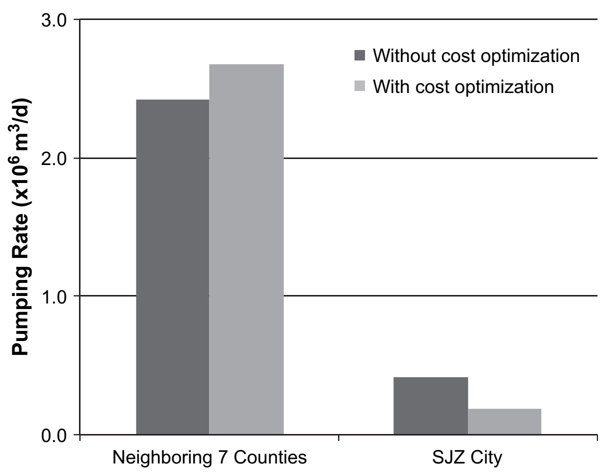

Figure 14. The redistribution of pumping resulting from the second optimization formulation.

The actual ground water depletion rate for urban land use is not known. However, it is known that urban water depletion is considerably less than the depletion from irrigation if all waste water is assumed to be treated and returned to its natural source (Kendy et al. 2007). In Luancheng County, the current average ET rate for cropland is 66 cm/year. If urbanization were realized, then a conservative estimate of the average ET rate (Kendy et al. 2003b) would be one-half of the average ET rate from cropland. Therefore, in the numerical model, additional recharge of 33 cm/year for Luancheng County can be added to account for reduced ET after adopting an urbanization strategy.

Here, it is assumed that urbanization was started from the beginning of the transient model (i.e., 1959) to see how the ground water level and aquifer storage would be changed under this assumption. The new ground water levels in 2004 are shown in Figure 15a as the black solid contour lines and are compared with the original ground water levels of 2004, which are shown as the gray dashed lines in the same figure. The figure shows that urbanization could help reduce the rapid ground water level decline and raise the ground water levels by about 3 to 15 m. Here, only the effect of the urbanization of Luancheng County was examined; if the urbanization extends to a larger area, its effect to mitigate the ground water table decline will be more pronounced.

Scenario 2—Implementation of the SNWT Project

The SNWT Project is a plan to divert water from the upper, middle, and lower reaches of the Yangtze River to the northern and northwestern parts of China. The SNWT includes three water diversion routes: the western, middle, and eastern routes, among which the middle and eastern routes will impact the NCP region. By the target year 2050, the total water volume to be diverted will be 45 billion cubic meters: 15 billion cubic meters from the eastern route, 13 billion cubic meters from the middle route, and 17 billion cubic meters from the western route (Ruan et al. 2004). Therefore, in this case, we took into account the potential effect of the SNWT project to determine its impact on the study area.

Because the diverted water is mainly for municipal and industrial use, it was assumed that all diverted water was applied to SJZ City and the pumping there was totally shut down, while the pumping activity in the counties remained unchanged. The predicted water level changes by the year 2055 are shown in Figure 15b,

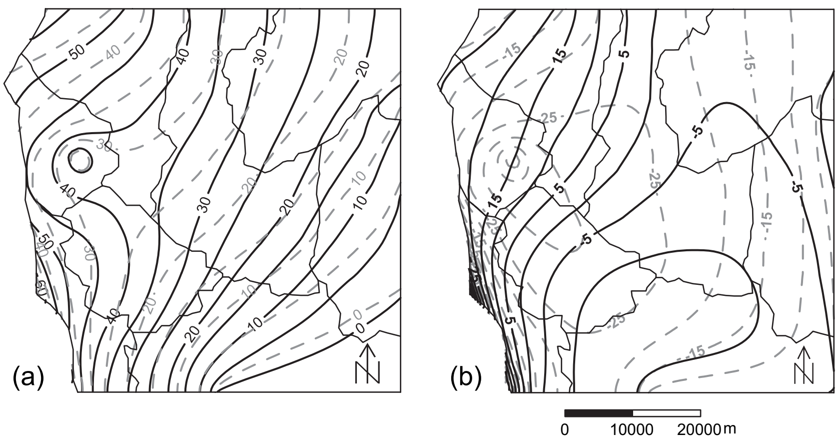

Figure 15. (a) Comparison of projected ground water levels in 2004 without (dashed) and with (solid) "urbanization" of Luancheng County and (b) comparison of projected ground water levels before (dashed) and after (solid) the SNWT project by the year 2055.

presented as the black solid lines, and the predicted ground water levels without adopting the SNWT project were shown in the same figure as the gray dashed lines. It can be seen that the SNWT project will reduce the rate of ground water level decline, especially in the area around SJZ City. In addition, the return flow from municipal and industrial water use could be reused through reallocation to agriculture, which will also improve the water use conditions in the counties that are not going to use the transferred water directly.

Nevertheless, on the regional scale, the transferred water quantity will be inadequate to fill the regional deficit between precipitation and ET. Therefore, the SNWT could provide a critical water supplement to some local areas but will not abate the ground water declines across the whole region (Kendy et al. 2007). To target the regional water shortages stemming from agricultural water use throughout the NCP, the combination of the previous two scenarios would be helpful. Those scenarios are mostly hydrogeologic in nature. There are many other possible scenarios, for example, fallowing agricultural land or converting to one crop per year, but those are beyond the scope of this study.

Discussion and Conclusions

The ground water flow model developed in this study was capable of reproducing historical ground water level changes since 1990 to a satisfactory degree. Flow budget analysis showed more outflow (pumping) than inflow (recharge), leading to significant depletion in aquifer storage. The formation of a large cone of depression in the water table near SJZ City indicated unsustainable ground water exploitation. The optimization model indicated that the redistribution of pumping could help temporally reduce the declining rate of water table.

But to cope with limited ground water resources radically, there are perhaps only two choices: (1) increasing water supply from outside sources and/or (2) reducing water consumption. The mega SNWT project is currently under construction in China and will bring outsource water and greatly relieve the water stress in the study area, but it will not start to deliver water for several more years (Qian and Zhang 2001). Further, due to the limited water volume from this project and its high costs, the transferred water will likely serve only the urban population and high-output industries. At the regional scale, the transferred water quantity will be much less than what is needed to fill the deficit between precipitation and ET. Therefore, instead of abating the ground water decline across the whole region, the SNWT project can only provide a critical water supplement to some local areas. The biggest water consumer in the NCP, the agriculture sector, which is currently using more than 70% of the water resources pumped in the NCP, will have to look for other solutions. Accelerated urbanization may be a solution, as suggested by Kendy et al. (2007), because urbanization consumes less water compared to irrigation. By assuming that Luancheng County was urbanized, the model showed that urbanization could reduce the rapid ground water decline and raise the ground water level by 3 to 15 m since the 1950s. However, such a mega social project involving tens of millions of people will certainly not be any easier than other approaches. New and even more complicated problems may surface during the process. Most important, the loss of a large grain production center may jeopardize China's food security and even destabilize the international food market.

Therefore, there is no single scenario alone that can solve the ground water depletion problem in the NCP. The sustainable development of ground water resources in the NCP requires an integrated system that considers water resources, land use, and climate change as well as the social and economic factors. This study is only the first step toward a comprehensive effort to develop effective management strategies that ensure long-term, stable, and flexible water supplies to meet growing municipal, agricultural, and industrial water demands in the NCP while simultaneously mitigating negative environmental consequences.

The models developed in this study are useful tools for analyzing the natural hydrologic processes and improving ground water management practices elsewhere affected by similar hydrologic and economic conditions. The numerical simulation is capable of quantifying the various components of the overall flow budget and evaluating the impacts of various management scenarios. The optimization modeling allows the determination of the maximum "sustainable pumping" that satisfies a series of prescribed constraints. It can also be used to minimize the economic costs associated with ground water development and management. It is noteworthy, however, that the "sustainable pumping" determined from balancing the hydrologic system may be meaningless if the human dimension and social pressures are not taken into account. Further study is needed to address the human dimension and social-economic issues of these ground water problems.

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References

Chen, W. 1999. *Hebei Ground Water.* Beijing, China: Seismological Press.

China Geological Survey. 2005. Report of ground water resources and environmental survey in China. Beijing, China: China Geological Survey.

Elvin, M. 2004. *The Retreat of the Elephants: An Environmental History of China*. New Haven, Connecticut: Yale University Press.

Engineering Computer Graphics Laboratory. 2005. Ground-water Modeling System Reference Manual (GMS v6.0). Provo, Utah: Brigham Young University.

Falkenmark, M., J. Lundquist, and C. Widstrand. 1989. Macroscale water scarcity requires micro-scale approaches: Aspects of vulnerability in semi-arid development. *Natural Resources Forum* 13, no. 4: 258–267.

Foster, S., H. Garduno, R. Evans, D. Olson, Y. Tian, W. Zhang, and Z. Han. 2004. Quaternary aquifer of the North China Plain—Assessing and achieving ground water resource sustainability. *Hydrogeology Journal* 12, no. 11: 81–93.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW-2000, The U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process. USGS Open-File Report 00-92. Reston, Virginia: USGS.

Harbaugh, A W., and M.G. McDonald. 1996. User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model. U.S. Geological Survey Open-File Report 96-485, Reston, Virginia: USGS.

Hebei Water Conservancy Office. 1996. *Hebei Water Conservancy Annals*. Shijiazhuang, Hebei: Hebei Water Conservancy Office.

Huai River Commission. 1998. *Hai He Gazetteer.* Beijing, China: China Water Power Press.

Hydrogeology and Engineering Geology Survey of Hebei Province (HEGS). 2004. Assessment of ground water resources in Shijiazhuang City. Shijiazhuang, Hebei: HEGS.

Hydrogeology and Engineering Geology Survey of Hebei Province (HEGS). 1992. Hydrogeological map of Hebei Province. Shijiazhuang, Hebei: HEGS.

Institute of Hydrogeology and Environmental Geology (IHEG). 1990. Optimization of water supply planning of the water resources system in Shijiazhuang City. Zhengding, Hebei: IHEG.

Institute of Hydrogeology and Environmental Geology (IHEG). 1988. Systematic analysis of water resources and the study of numerical model: Application on the fluvial plain of Hutuo River in Shijiazhuang. Zhengding, Hebei: IHEG.

Jia, J. 2002. Ground water system evolution and sustainable use: A case study of Shijiazhuang City and Luancheng County. Ph.D. diss., Chinese Academy of Sciences, Beijing, China.

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

Kendy, E., Y. Zhang, C. Liu, J. Wang, and T.S. Steenhuis. 2004. Ground water recharge from irrigated cropland in the North China Plain: Case study of Luancheng County, Hebei Province, 1949–2000. *Hydrologic Process* 18, 2289–2302.

Kendy, E., P. Gerard-Marchant, M.T. Walter, Y. Zhang, C. Liu, and T.S. Steenhuis. 2003a. A soil-water-balance approach to quantify ground water recharge from irrigated cropland in the North China Plain. *Hydrologic Process* 17, 2011–2031.

Kendy, E., D.J. Molden, T.S. Steenhuis, and C. Liu. 2003b. Policies drain the North China Plain: agricultural policy and ground water depletion in Luancheng County, 1949–2000. IWMI Research Paper 71. Colombo, Sri Lanka: IWMI.

Lin, X., and Z. Liao. 1995. *Ground Water Management*. Beijing, China: Geological Press.

Liu, C., J.J. Yu, and E. Kendy. 2001. Ground water exploitation and its impact on the environment in the North China Plain. *Water International* 26, no. 2: 265.

Ministry of Water Resources of PRC, World Bank, and AusAID. 2001. China agenda for water sector strategy for North China, Vol. 1: Summary Report. Report no. 22040-CHA. Beijing, China.

Postel, S. 1999. *Pillar of Sand: Can the Irrigation Miracle Last?* New York: W.W. Norton & Company Inc.

Qian, Z., and G. Zhang. 2001. Report collection of sustainable water development strategies of China. Beijing, China: China Water Resources and Hydropower Press.

Ruan, B., L. Wang, and L. Chen. 2004. Brief introduction to south-to-north water transfer. American Society of Civil Engineers, doi: 10.1061/40737(2004)117.

Zheng, C., and Wang, P.P. 2003. MGO—A Modular Ground water Optimizer Incorporating MODFLOW/MT3DMS. Tuscaloosa, Alabama: University of Alabama.