
Optimizing groundwater development strategies by genetic algorithm: a case study for balancing the needs for agricultural irrigation and environmental protection in northern China

Jianfeng Wu · Li Zheng · Depeng Liu

Abstract Gaoqing Plain is a major agriculture center of Shandong Province in northern China. Over the last 30 years, the diversion of Yellow River water for intensive irrigation in Gaoqing Plain has led to elevation of the water table and increased evaporation, and subsequently, a dramatic increase in salt content in soil and rapid degradation of crop productivity. Optimal strategies have been explored, that will balance the need to extract sufficient groundwater for irrigation (to ease the pressure on diverting Yellow River water) with the need to improve the local environment by appropriately lowering the water table. Two simulation-optimization models have been formulated and a genetic algorithm (GA) is applied to search for the optimal groundwater development strategies in Gaoqing Plain, while keeping the adverse environmental impacts in check. Compared with the trial-and-error approach of previous studies, the optimization results demonstrate that using an optimization model coupled with a GA search is both effective and efficient. The optimal solutions identified by the GA will provide Gaoqing Plain with the blueprints for developing sustainable groundwater abstraction plans to support local economic development and improve its environmental quality.

Résumé La Plaine de Gaoqing est un centre agricole majeur de la Province de Shandong au nord de la Chine. Au cours des 30 dernières années, la dérivation de l'eau de la Rivière Jaune pour l'irrigation intensive de la Plaine de Gaoqing a généré une élévation du niveau piézométrique et un accroissement de l'évaporation, causant une augmentation dramatique des concentrations en sels dans les sols et une dégradation rapide de la productivité des cultures. Des stratégies optimales ont été examinées, pour équilibrer les besoins en eau souterraine pour l'irrigation (afin de soulager la pression sur la dérivation de la Rivière Jaune) avec la nécessité d'améliorer l'environnement local en rabattant adéquatement le niveau piézométrique. Deux modèles de simulation-optimisation ont été formulés et un algorithme génétique est mis en œuvre pour rechercher les stratégies d'utilisation optimale des eaux souterraines sur la Plaine de Gaoqing, en surveillant les effets inverses sur l'environnement. Comparés à l'approche par approximations successives des études précédentes, les résultats de l'optimisation démontrent que l'utilisation couplée d'un modèle d'optimisation et d'une recherche avec un algorithme génétique est à la fois effective et efficace. Les solutions optimales identifiées par l'algorithme génétique donneront à la Plaine de Gaoqing le schéma directeur pour développer des politiques durables d'exploitation des eaux souterraines, afin de supporter le développement économique local et améliorer ses qualités environnementales.

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Resumen La Llanura de Gaoqing es un centro de agricultura muy importante de la Provincia de Shandong en China norteña. Durante los últimos 30 años, la desviación de agua del Río Amarillo para la irrigación intensiva en la Llanura de Gaoqing, ha llevado a la elevación del nivel freático y esto ha incrementado la evaporación, y como consecuencia, esto resultó en un aumento dramático en el contenido de sal en el suelo y en la degradación rápida de productividad de las cosechas. Se han explorado las mejores estrategias, tal que equilibren la necesidad de extraer el agua subterránea suficiente para la irrigación (para aliviar la presión en desviar el agua del Río Amarillo), con la necesidad de mejorar el ambiente local bajando el nivel freático apropiadamente. Se han formulado dos modelos de simulación-optimización y un algoritmo genético (GA) se aplica para buscar las estrategias de desarrollo óptimas del agua subterránea en la Llanura de Gaoqing, mientras se mantienen los impactos medioambientales adversos bajo observación. En compara-

ción con las técnicas de ensayo-y-error de estudios anteriores, los resultados de esta optimización demuestran que usando un modelo de optimización acoplado con una búsqueda mediante GA, es tanto eficaz como eficiente. Las soluciones óptimas identificadas por el GA, proporcionarán las bases para desarrollar los planes de extracción sustentable del agua subterránea en las llanuras de Gaoqing, los cuales darán apoyo al desarrollo económico local y mejorarán su calidad medioambiental.

Keywords Over-abstraction · Yellow River · Groundwater recharge/water budget · Simulation-optimization model

Introduction

Gaoqing Plain is a major agriculture center of the Shandong Province in northern China. It is located at the lower reaches of the Yellow River basin (Fig. 1a), and covers an area of 847 km². Over the last 30 yrs, Gaoqing Plain has achieved significant increases in its grain and cotton production. Much of this growth was made possible by the development of an intensive irrigation program. According to the Water Resources Management Office of Gaoqing County (1997), the total water consumption in this area has topped 200 million m³ annually in the last decade, of which over 80% was used for agricultural irrigation. The total area irrigated in Gaoqing Plain amounts to over 45,360 ha. The main crops growing here are winter wheat and summer maize. With a monsoon climate in the North Temperate Zone, Gaoqing Plain has an average rainfall of 580 mm/yr, and receives over 70% of its rainfall during the summer monsoon season from June to September. The precipitation, however, plays a small part in Gaoqing Plain's water supply. Over 80% of the water consumed here has come from diverting the Yellow River water.

The diversion of Yellow River water has produced high agricultural yields and increased economic wealth but has also brought many undesirable environmental consequences. The infiltration of irrigation water has caused the water table to rise and increased evaporation, which has led to an increase in the salt content in the soil and decrease in crop productivity (Department of Earth Sciences of Nanjing University, and Water Resources Management Office of Zibo City 1997). The heavy use of water from the Yellow River, one of the most severely silted rivers in the world, for irrigation also brought in more than 30 kg of sandy silt to local farmland with every cubic meter of water applied, which amounts to more than 5 million metric tons of sandy silt per year over Gaoqing Plain. The accumulation of sandy silt has reduced the productivity of farmland and caused other environmental nuisances, for example, dust in the air during the high wind season. Further, the reliance of the local agricultural economy on the diversion of Yellow River water has become an increasingly unsustainable practice. Due to excessive water diversion and consumption along its

reaches and a drier than normal climate condition in recent decades, Yellow River has experienced frequent cutoffs since 1972. Especially during 1990–1998, the river has been cut off every year with increasing duration and distance along its main channel (Cai and Rosegrant 2004). Gaoqing Plain is now under great administrative and economic pressure to cut back on its annual water intake from Yellow River. To sustain the agricultural outputs and local economy, municipal authorities have to look for water from other sources, and are now contemplating tapping into the local groundwater resources.

The groundwater resources are almost undeveloped in Gaoqing Plain. Currently, the abstraction of groundwater makes up less than 10% of local water supplies. To increase the water supply from the underground source will definitely ease the pressure to divert the Yellow River water. Further, past heavy irrigation with surface water (without artificial drainage in most places) has led to a very shallow water table, thus significant discharge of groundwater via direct evaporation. Stepping up groundwater irrigation will lower the water table, reduce the amount of groundwater evaporation, and help to alleviate and remedy the soil salinization problems (Hu et al. 2005; Wang et al. 2004; Zhen et al. 2005). However, the development of groundwater resources for irrigation is not without its own perils. Two hundred kilometers to the north, in the heart of the North China Plain, a similar situation was encountered in the early 1970s, and decisions were made to abstract the groundwater for irrigation. Now, within 30 yrs, the intensive pumping of groundwater for irrigation has lowered the water table from the original 2 m below ground surface to 20–30 m below ground surface, and caused a series of devastating environmental problems, including groundwater depletion, the drying up of rivers and streams, land subsidence, and intrusions of sea water, saline water and contaminants (Liu et al. 2001; Liu and Xia 2004; Han 2003; Foster et al. 2004; Kendy et al. 2003). Of particular concern in Gaoqing Plain is that around the area near its southern border, the Xiaoqing Stream (Fig. 1a) could turn from a gaining stream into a losing stream if the water table was lowered too much by the pumping, and the groundwater flow could reverse its direction. Recent analyses in various reports have found that the Xiaoqing Stream has been severely polluted by a whole array of heavy metals, chlorinated organic compounds and other toxic contaminants (Tian et al. 1993; Zhang 1997; Miao et al. 1999; Su and Sun 2002; Lu et al. 2003; Ma et al. 2003). The reverse of flow direction and the recharge of the highly polluted Xiaoqing Stream water into the aquifer would degrade the groundwater resource and deliver an irreversible loss to the local community. Therefore, the development of groundwater resources for irrigation should proceed with caution. The goal of current research is to explore the proper strategies that will balance the needs for extracting sufficient irrigation water and protecting local environment and natural resources.

Groundwater modeling is a very effective tool for simulating aquifer response to groundwater abstraction

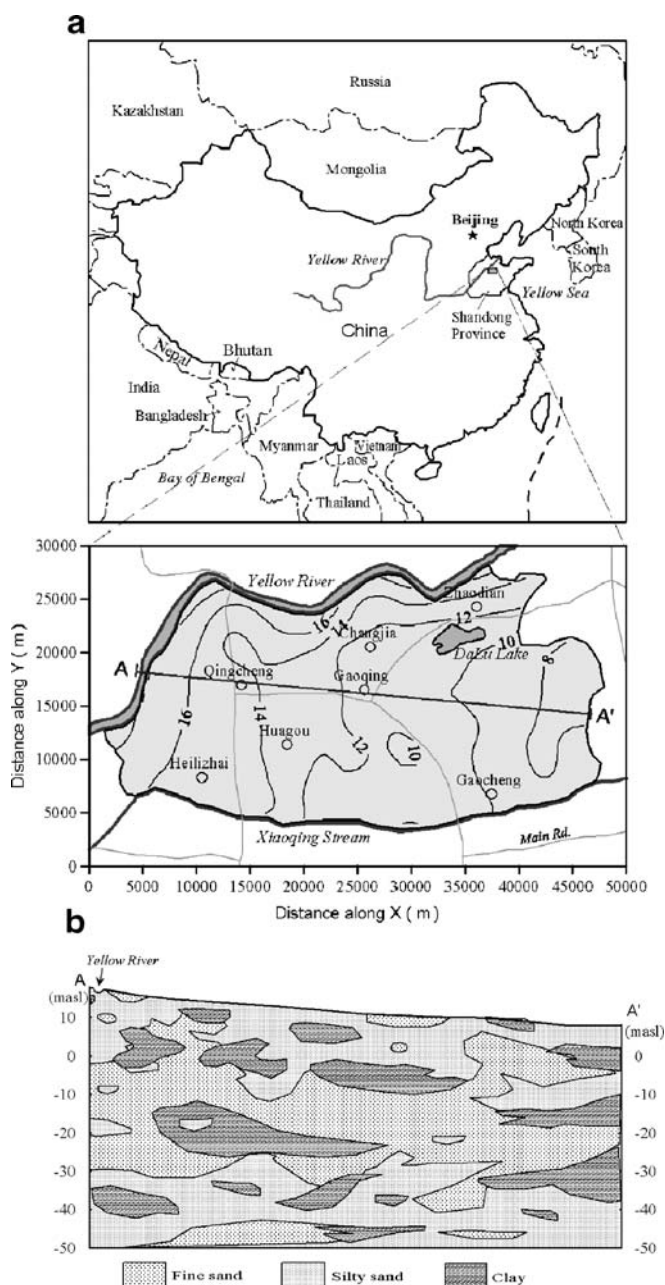


Fig. 1 a The schematic geography and geology of Gaoqing Plain and its location in northern China. The *gray shaded* domain represents the study area of interest, the Gaoqing County. The contours (in masl) shape the outline of topography in Gaoqing Plain. The *small circles* denote towns in Gaoqing Plain. b The cross section map demonstrates the alluvial deposits of the aquifer along the section plane A-A'

and evaluating the subsequent environmental impacts. Combining such a groundwater simulation with an optimization model, one can seek to maximize the benefits of groundwater irrigation and minimize the adverse environmental impacts. However, such a formulation normally results in a complex nonlinear multi-dimensional optimization problem; the search for an optimal solution for such a complex function is not a trivial task. The conventional gradient-based search schemes may converge to a local, instead of the global optimal solution.

The evolutionary search methods such as genetic algorithms (GAs), are often the preferred choices (Cai et al. 2001). The genetic algorithm (GA) is a directed random search technique, and capable of finding the globally optimal or near-optimal solution in complex multi-dimensional search spaces. In recent years, the GA technique has been shown to be flexible enough to accommodate explicit complex groundwater optimization problems. Many authors have reported the applications of GAs in various water resources planning and design projects, including parameter identification (Karpouzou et al. 2001; Prasad and Rastogi 2001), groundwater pump-and-treat remediation (McKinney and Lin 1994; Huang and Mayer 1997; Wang and Zheng 1997, 1998), contamination remediation/containment (Ritzel et al. 1994; Aly and Peralta 1999a, b; Erickson et al. 2002; Maskey et al. 2002; Bayer and Finkel 2004; Hilton and Culver 2005), and plume monitoring (Reed et al. 2000a; Wu et al. 2005).

In the current study, the Gaoqing Plain's conflicting needs for groundwater development and environmental protection are formulated into a groundwater optimization problem. Under two different optimization scenarios (model-I and model-II), as described in the following section, a GA is applied to search for the optimal groundwater development strategies that will maximize the agricultural and environmental benefits of groundwater exploitation in Gaoqing Plain, while keeping the adverse environmental impacts in check. The results are compared with the work of Wu et al. (1998), in which a trial-and-error approach was used to search for the best groundwater development strategies for Gaoqing Plain. It is demonstrated that the approach reported here, of using an optimization model coupled with a GA search, is both effective and efficient. The optimal solutions identified by the GA search will provide Gaoqing Plain with blue prints for developing sustainable groundwater abstraction plans to support local economic development and improve its environmental quality.

Geology and hydrogeology of Gaoqing Plain

The Gaoqing Plain is a part of the alluvial deposits of the Yellow River and comprises thick Tertiary and Quaternary sediments. The superficial sedimentary layer is about 60 m in thickness, mainly comprises silty sand and fine sand, and contains abundant pore-space water (Fig. 1b). The overall topography of the area is flat, descending slowly from NW–SE with a gradient of about 1/7,000 and an average altitude of 12 m above sea level (masl). The local climate is described above.

Due to the smooth relief of the land surface and the shallow water table (Fig. 2), the dynamics of the local groundwater system in the unconfined aquifer are dominated by the vertical water exchange, with very slow movement in the horizontal direction. The aquifer is mainly recharged by the infiltration of precipitation and irrigation water, which account for over 91% of the total recharge. The recharge to the local aquifer by lateral

seepage from the Yellow River is insignificant in comparison. Most of the current water table in Gaoqing Plain lies within 2–3 m of the ground surface (Fig. 2b). Eighty five percent of the total discharge from the shallow aquifer, therefore, consists of the direct evaporation and evapotranspiration of the phreatic water. The discharge from the aquifer into the Xiaoqing Stream in the south is less than 1%. More details on the water budget of the local aquifer can be found in Wu et al. (1998) and Fig. 9a and b.

Methodology

A simulation–optimization (S/O) model was developed to perform an optimal solution search. The S/O model includes three components: (1) a groundwater flow model for simulating hydrological responses of the aquifer under various groundwater pumping schemes, (2) a tradeoff estimator for balancing the conflicting agricultural and environmental interests, and (3) a GA based technique for searching global optimal solutions. Figure 3 illustrates the framework of the S/O model developed.

Flow simulation model

The first part of the S/O model is a groundwater flow model for simulating the hydraulic responses of the study site under various groundwater abstraction scenarios. The groundwater flow model for the Gaoqing Plain was developed by Wu et al. (1998) and was available for use in the current study.

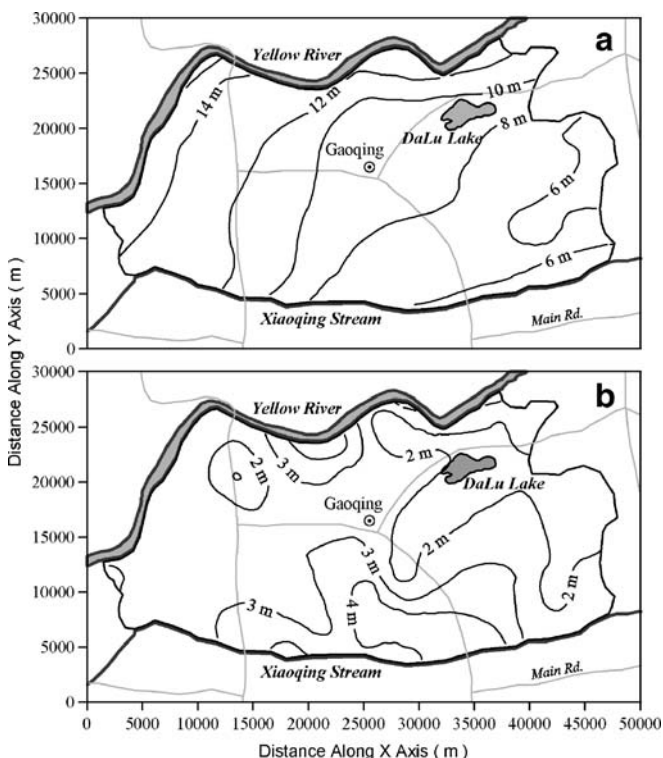


Fig. 2 Contours of the **a** current water table (masl), and **b** depth to water table (meters below ground surface), for the Gaoqing Plain aquifer

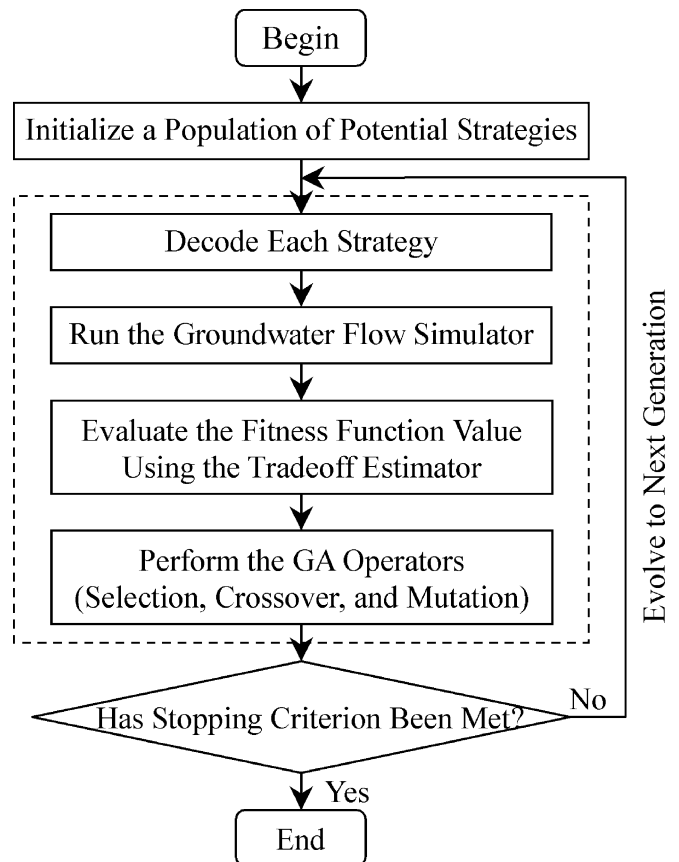


Fig. 3 The flowchart of the S/O model used in this study for identifying the optimal groundwater development strategy. The processes within the dashed block denote one iteration or generation of the evolution

For the completeness of presentation, the Wu et al. (1998) flow model is briefly recapitulated here.

The unconfined aquifer in Gaoqing Plain (847 km² in size and less than 60 m in depth) is modeled as a two-dimensional isotropic groundwater system. The governing equation for the groundwater flow in this heterogeneous aquifer is given as:

$$\frac{\partial}{\partial x} \left(K(H - B_t) \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(K(H - B_t) \frac{\partial H}{\partial y} \right) + \alpha P + \beta I - \gamma E_0 - Q_a = S_y \frac{\partial H}{\partial t} \quad (1)$$

where K is the hydraulic conductivity ($L T^{-1}$); H is the hydraulic head (L); B_t denotes the bottom elevation of the aquifer (L); α is the recharge coefficient of precipitation infiltration, dimensionless; P is the precipitation intensity ($L T^{-1}$); β is the coefficient of irrigation return flow, dimensionless; I is the irrigation intensity ($L T^{-1}$); γ is the evaporation coefficient of groundwater, dimensionless; E_0 is the intensity of evaporation from water surface ($L T^{-1}$); Q_a is the intensity of groundwater pumping ($L T^{-1}$); S_y is the specific yield of the aquifer, dimensionless; and t is time (T).

As shown in Fig. 1a, the Yellow River forms the north and northwest boundary of the study domain, and the Xiaoqing Stream forms the south boundary. In the model reported here, the specified flux boundary condition was used to represent the recharge along the Yellow River because the riverbed sediment in contact with the underlying aquifer is semi-permeable. Considering that the potential pumping proposed by the optimization model may lead to the reverse of the current flow direction along the Xiaoqing Stream, the general-head boundary is used for the south boundary. Along the modeling domain's east boundary, a specified flux of 0.1 cm/yr estimated from the aquifer properties and the regional gradient of groundwater flow by Shandong Province Institute of Geology and Mineralogy Engineering (1993) is used to represent the regional groundwater flow flux toward the east. As a result, the annual outflow at the east boundary is about $1.4 \times 10^6 \text{ m}^3$, accounting for less than 1% of the total outflow (annually $1.8 \times 10^8 \text{ m}^3$) in the water budget. The west boundary is the Gaoqing County divide, where the horizontal groundwater flux is very small and, therefore, is treated as a zero flux boundary.

In the current study, the groundwater flow model developed by Wu et al. (1998) was adopted, which uses the MODFLOW code (McDonald and Harbaugh 1988). The discretization of the modeling domain includes 101 columns and 61 rows, with uniform grid spacing of 500 m, which results in 3,786 active cells. In the groundwater flow model, a simple zonation approach was adopted for the model parameterization, based on results from the published hydrogeological investigation reports (Shandong Province Institute of Geology and Mineralogy Engineering 1993; Department of Earth Sciences of Nanjing University, and Water Resources Management Office of Zibo City 1997). All the values for the model parameterization were determined based on the experiment data collected on 156 field sites in Gaoqing

Table 1 The values of the parameters used in the modeling of groundwater dynamics^a

Parameter zone No.	Hydraulic conductivity, m/d	Specific yield, dimensionless	Precipitation infiltration coefficient, dimensionless
1	6.75	0.05	0.32
2	10.91	0.06	0.36
3	3.38	0.05	0.32
4	7.54	0.05	0.30
5	12.94	0.05	0.32
6	12.89	0.06	0.35
7	9.24	0.02	0.28
8	8.23	0.05	0.30
9	11.90	0.05	0.32
10	11.29	0.02	0.25
11	8.35	0.05	0.32
12	8.00	0.02	0.28
13	6.17	0.05	0.32
14	7.28	0.05	0.30
15	11.66	0.06	0.30
16	5.86	0.05	0.15
17	3.38	0.05	0.30

^a Adapted from Wu et al. (1998).

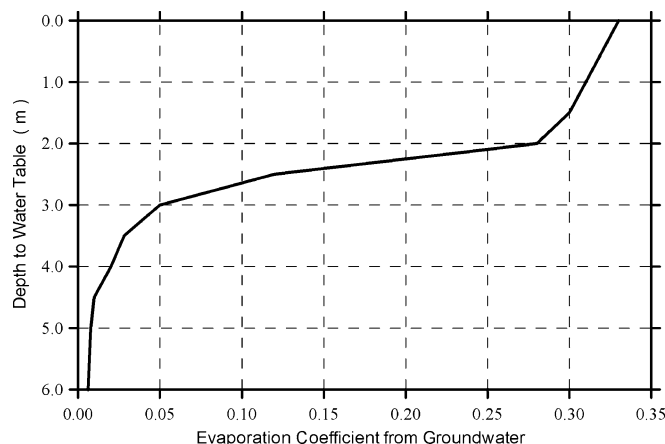


Fig. 4 The correlation curve of the coefficient of evaporation versus the depth to the water table (adapted from Wu et al. 1998)

Plain from 1986 to 1993, conducted by Shandong Province Institute of Geology and Mineralogy Engineering (1993). The model domain was divided into 17 zones for the parameterization of hydraulic conductivity (K), precipitation infiltration coefficient (α), and specific yield (S_y). The estimated K value ranges from 3.38 to 12.94 m/d with a mean of 8.57 m/d; the α value ranges from 0.15 to 0.36 and S_y value ranges from 0.02 to 0.06. The detailed parameter values assigned for each of these 17 zones are given in Table 1, adapted from Wu et al. (1998). Also, a uniform coefficient of irrigation return flow β of 0.24 was specified by the in situ artificial recharge test results provided in those published reports (Shandong Province Institute of Geology and Mineralogy Engineering 1993; Department of Earth Sciences of Nanjing University, and Water Resources Management Office of Zibo City 1997). Since there are no sufficient observation data available for performing reliable inverse modeling, the model validation was made by approximately analyzing the rationality of flow budget and water balance in detail (Wu et al. 1998). Considering that the dynamics of the local groundwater system in the aquifer is dominated by the vertical water exchange with a very slow movement in the horizontal direction, and the focus of this study is to demonstrate the feasibility of a balanced groundwater development strategy such a model validation is reasonable and then the flow model can be used for coupling with the optimization model.

In the model reported here, the vertical influx due to both irrigation and precipitation is simulated using the Recharge Package in MODFLOW. The previously mentioned reports (Shandong Province Institute of Geology and Mineralogy Engineering 1993; Department of Earth Sciences of Nanjing University, and Water Resources Management Office of Zibo City 1997) also showed that the evaporation coefficient of groundwater (γ) in this area is correlated with the depth to the water table, as illustrated in Fig. 4, where the correlation was conducted from the experiment data collected at 100 different sites in Gaoping Plain from 1986 to 1992, regardless of the land surface being either bare or planted with crops. Note that the evaporation defined here is actually

composed of both evaporation and evapotranspiration. Here, this relationship is used to model the direct evaporation from shallow groundwater using the Evapotranspiration Package in MODFLOW. There are currently no large centralized pumping activities and the groundwater is mainly used for agriculture irrigation in this area, thus the groundwater pumping component was simplified as the areal outflow, or the reverse areal recharge. Accordingly, the simulation of groundwater pumping integrated with irrigation and precipitation recharge can be implemented using the Recharge Package in MODFLOW. However, here, the part that is reverse areal recharge by groundwater pumping is treated as a potential pumping well in each active cell using the Well Package in MODFLOW. Then there are 3,786 potential pumping wells located in the active cells of the model. Based on the local aquifer properties and the geographic locations, the Gaoqing Plain is divided into six subdomains for groundwater pumping, each of which would be assigned a groundwater pumping strategy that represents the total pumping rates from the potential pumping wells in the corresponding subdomain. To explore the optimal groundwater pumping scheme, one potential well in each subdomain is selected as a candidate for the GA search; and the others are the dependent wells. The pumping rate from each candidate well would be identical to that from its dependent wells due to the uniform discretization of the modeling domain. Therefore, there are only six decision variables (total pumping rates in six subdomains) in the following S/O model even though the number of the candidate wells and their dependent wells is up to 3,786 in all.

Optimization model

Considerations for optimization model setup

Firstly, to set up the optimization model, the optimization model should honor the total water balance. Secondly, the model should take account of the current water table, which is shallow, and consider that the direct evaporation from phreatic water is the most significant component of the groundwater discharge. One goal of the current study is to capture most of this nonbeneficial evaporation and use it for irrigation while keeping other adverse environmental impacts in check. The optimization model, therefore, will aim at lowering the water table by increasing groundwater pumping, under various hydrological constraints, thus reducing the direct evaporation. Thirdly, the model should consider that irrigation varies with the seasons. Spring season needs much more irrigation than other times, and the irrigation needed during the summer monsoon season would be minimal. Therefore, the groundwater development strategies should also reflect the seasonal variation in water demand. On the other hand, to simplify the matter, the optimal yearly pumping schedule in the current study, once identified, will stay

the same from year to year for the entire management period, i.e., the next 15 yrs. Fourthly, precipitation is the primary source of recharge for the unconfined aquifer. Future climatic changes (i.e., the changes in precipitation events) could directly impact the results of the optimization model. Fifthly, although the annual water diversion from the Yellow River is currently limited at a maximum amount of 180 million m^3 , as explained previously, there is great pressure to reduce the use of Yellow River water and the model will need to take account of this. In fact, it is possible to experience more future Yellow River cut offs and then the availability of Yellow River water would be completely eliminated. In searching for the optimal groundwater pumping strategy, one assumes that the combined use of groundwater and Yellow River water will meet the water demand, which is set at the current level of 200 million m^3/yr for the entire management period, regardless of the availability of water diverted from Yellow River. As long as the total amount of applied irrigation water stays the same and the total water supply meets the water demand in the area, the recharge provided by the irrigation water will be the same, and thus the variation of Yellow River water diverted will not affect the optimization results. If indeed the allowable volume of diverted Yellow River water fell below the minimum amount required to meet the local water demand, there will be implications beyond just managing the groundwater pumping, which will be discussed later. Finally, both the national policy and the health of the Yellow River eco-environment discourage the diversion of Yellow River water, and yet diverting surface water for irrigation is still a much less costly option than pumping groundwater; therefore, the formulation of the optimization can go in two ways. On one hand, one may try to maximize the amount of groundwater pumping within environmental constraints, so that as little Yellow River water as possible is used to meet the local water demand. On the other hand, one may minimize the groundwater pumping under all constraints, and use as much Yellow River water as allowed by the regulation to achieve the minimum cost. In the following sections, two optimization models are formulated, which search for optimal groundwater development strategies for both scenarios.

Optimization model formulation

Taking into account the above considerations as well as the local aquifer properties and the land use/land cover conditions, the Gaoqing Plain was divided into six subdomains (Fig. 5), each of which would be assigned a different groundwater pumping scheme. For example, subdomain 1 is close to the Yellow River and subdomain 4 is close to the Xiaoqing Stream. Comparatively, the aquifers have higher hydraulic conductivities in subdomains 2, 3 and 5 than in subdomain 6. Moreover, the division of the six subdomains is also influenced by the initial distribution of the depth to the water table. Note that Fig. 5 shows two subdomain 3 areas because there are

quite similar aquifer properties and land cover conditions for these two subdomains and they are assigned to the same groundwater exploitation intensities. Then the optimization models were formulated as follows:

$$\text{Maximize } J = \sum_{t=1}^{NT} \sum_{i=1}^{ND} Q_i^t \cdot NY \quad (2)$$

$$\text{or minimize } J = \sum_{t=1}^{NT} \sum_{i=1}^{ND} Q_i^t \cdot NY \quad (3)$$

$$\begin{aligned} \text{subject to } H_k^{\text{lower}} &\leq H_k^{t,\tau} \leq H_k^{\text{upper}}, \quad t \\ &= 1, 2, \dots, NT; \tau = 1, 2, \dots, NY \end{aligned} \quad (4)$$

$$H_j^{\text{in}} - H_j^{\text{out}} \geq \Delta H_{\min}, \quad j = 1, 2, \dots, NG \quad (5)$$

$$\begin{aligned} H_k^t &= \text{trans}(Q_1^t, Q_2^t, \dots, Q_{ND}^t)^{\tau}, \quad t = 1, 2, \dots, NT; \tau \\ &= 1, 2, \dots, NY \end{aligned} \quad (6)$$

In Eqs. (2) and (3), J is the management objective: the total groundwater withdrawals from all subdomains during the entire management period; ND is the total number of management subdomains ($ND=6$); NT is the number of time steps within a single hydrographic year. In this study, a hydrographic year is divided into three nonuniform time steps, namely the spring irrigation period or drought period (SI, from March to June), the rainy season period (RS, from July to September), and the winter irrigation period (WI, from October to next February). Q_i^t is the pumping rate adopted for the i th subdomain at the specific time step t ($i=$

1, 2, ..., 6; $t=1, 2, 3$), representing the total pumping rates from the candidate well and its dependent wells; and NY is the number of hydrological years included in the entire management period ($NY=15$). As explained earlier, the pumping schedule Q_i^t may vary during the different seasons, but will stay the same in a specific season for all years of the entire management period.

Equation (4) gives the first constraint, which specifies the upper and lower bounds for hydraulic heads. $H_k^{t,\tau}$ denotes the hydraulic head at control point k at time t in the τ th hydrological year of the entire management period; H_k^{upper} is the upper bound and H_k^{lower} the lower bound for hydraulic heads. For groundwater development in Gaoqing Plain, the upper and lower bounds are specified as 3 and 5 m below ground surface, respectively. When the water table exceeds H_k^{upper} , the direct evaporation from phreatic water will become significant, which will lead to significant nonbeneficial water loss and soil salinization. On the other hand, the declining of water table beyond H_k^{lower} will indicate that the pumping intensity has exceeded the aquifer's recharge capacity, and further pumping may cause groundwater depletion and other adverse environmental impacts such as land subsidence etc. The second constraint given by Eq. (5) requires that the hydraulic gradient along the south boundary will always be positive toward the Xiaoqing Stream, thus producing a hydraulic barrier for containing the contaminated water in the stream. H_j^{in} and H_j^{out} are the head pair at location j , with H_j^{out} being closer to the stream than H_j^{in} ; $\Delta H_{\min}$ is a small positive value; and NG is the total number of head pairs. Eq. (6) is the third constraint which tracks the hydraulic head changes from one time step to the next using *trans*, the groundwater flow simulator.

Eqs. (2) and (4)–(6) define an optimization problem (model-I) that aims at maximizing the potential pumping of groundwater for Gaoqing Plain while lowering the water table to an appropriate level, and thus minimizing the use of Yellow River water for meeting the local water need. Equations (3) and (4)–(6) define another optimization model (model-II) for minimizing the groundwater exploitation while guaranteeing the water demands for Gaoqing County with as much surface-water diversion as permitted, and improving the environment by appropriately lowering the water table.

The solutions to the above models, model-I and model-II, can be obtained using different optimization techniques. The linear programming method is not applicable in this case because the unconfined groundwater flow is a nonlinear problem. Moreover, the gradient-based nonlinear search algorithms may not be a viable choice because they may terminate at a local optimal solution instead of the global optimal solution, due to the apparent nonconvexity of the unconfined groundwater problem. To search for the global optimal or near-optimal solutions for this multi-dimensional complex nonlinear problem, the evolutionary search techniques are usually the preferred choices (Cai et al. 2001). In the current study, a GA search technique is used for this purpose.

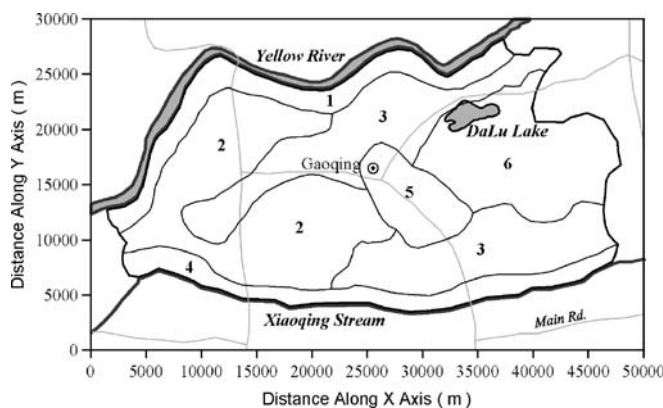


Fig. 5 Zonation map (subdomains) for assigning potential groundwater exploitation intensity

Implementation of the genetic algorithm

The GA is a directed random search technique invented by Holland (Goldberg 1989). It can find the global optimal solution in complex multi-dimensional search spaces. A GA is modeled based on the theory of Darwinian evolution, or the “survival of the fittest.” A simple GA consists of three operators known as selection, crossover and mutation. The technique begins by randomly generating a set of individuals within one population, with each individual representing an alternative solution to a given optimization problem. After the processes of genetic operation, a new population, or generation, arises from the previous generation through competition based on the individual’s fitness evaluation. The new population, retaining the same size as that of the previous population, is expected to contain individuals with improved fitness values because the use of probabilistic transition rules in the operation makes the fittest individuals have the highest probability of being selected to enter the next generation. As the generation evolved constantly, the optimal or near-optimal solution will be obtained. Detailed descriptions of GAs can be found in many references (e.g., Goldberg 1989; Sen and Stoffa 1995; Pham and Karaboga 2000). In the current study, the GA scheme presented by Wu et al. (2005) was adopted, which was implemented into the groundwater development problem described above to search for the optimal strategies that will balance needs for agricultural irrigation and environmental protection.

To find the optimal solutions to the problems above, first, the constrained model is modified to an unconstrained fitness measure by adding the amount of constraint violations to the objective function as penalties:

$$F = J \mp \sum_{i=1}^{NC} V_i \quad (7)$$

and

$$V_1 = \text{coeff}_1 \cdot \max \left(0, \frac{H^{\text{lower}} - H_i^t}{H^{\text{lower}}}, \frac{H_i^t - H^{\text{upper}}}{H^{\text{upper}}} \right) \quad (8)$$

$$V_2 = \text{coeff}_2 \cdot \max \left(0, \frac{\Delta H_{\min} - (H_j^{\text{in}} - H_j^{\text{out}})}{\Delta H_{\min}} \right) \quad (9)$$

where F is the fitness value; the middle operator on the right-hand side of Eq. (7) will take a minus sign for the maximization model (model-I) and a plus sign for the minimization model (model-II); V_i ($i=1, 2$) are the penalty amount of constraint violation with respect to the constraints on groundwater level in Eq. (4) and hydraulic gradient direction in Eq. (5); NC is the number of constraint violations ($NC=2$); and coeff_i ($i=1, 2$) are penalty coefficients. The constraint 3, Eq. (6), is strictly followed by the execution of the groundwater flow model.

The decision variables, Q_i^t , for the management model are analogous to biological genes, and are represented by coded structures including binary coding and real number representation. A strategy (a set of Q_i^t) in the search space is represented by a collection of genes. A set of strategies (solutions) at a certain iteration (generation) represents a population. In this GA search, the minimum precision of the decision variables (pumping rates) was set at $5,000 \text{ m}^3/\text{d}$.

During the GA operation in this study, all of the GA operators and parameters were set to be identical: the population size, M , was 500; the number of generations, 120; the crossover probability, P_c , and mutation probability, P_m , 0.80 and 0.05, respectively. As the generation evolves, the fitness measure as stated in Eq. (7) is improved gradually until the optimal or near-optimal solution (pumping strategy) is obtained. Similar to results given in Wu et al. (2005), it was found that a slightly higher P_m works better even though P_m was normally recommended to be the inverse of the population size ($1/M$) (Reed et al. 2000a, b). It was also assumed that the penalty coefficients, coeff_i ($i=1, 2$), in Eq. (7) are identical and equal to $1.0 \times 10^{10} \text{ m}^3$ for the entire 15-yr management period. The current analyses do not address the impacts of varying coeff_i ($i=1, 2$) values on the optimization results because the GA used in this study is identical to that introduced in Wu et al. (2005). Readers may refer to the work of Wu et al. (2005) for more discussions on this topic.

Results and discussion

As mentioned above, the amount and distribution of precipitation will affect the optimization results for the groundwater development strategies. Based on the analyses of the precipitation data from 1956 to 2002 obtained from the Gaoqing County Meteorological Bureau (Wu et al. 1998), the monthly precipitation of 1975–1989 was selected as the input data for the future 15-yr management period in this study. As shown in the previous analyses (Wu et al. 1998), this series is representative of the precipitation events in this area, which has a minimum annual average precipitation of 278.5 mm in 1989, a maximum of 680.7 mm in 1984, and an overall mean of 521.39 mm. The previously described optimization procedure was applied to both model-I and model-II (as defined in section Optimization model formulation) and obtained two sets of optimal groundwater pumping strategies for Gaoqing Plain. Given in Fig. 6 are optimal groundwater exploitation intensities (EIs), identified by model-I and model-II, respectively, for three different seasons in the six subdomain zones of Gaoqing Plain. The EI is defined by the pumping rate divided by the size of the associated zone, and has a dimension of a thickness per unit time (L/T). Also given in Fig. 6 for comparison are corresponding EIs given by the trial-and-error method in a previous study (Wu et al. 1998). The general distributions of groundwater exploitation intensities are

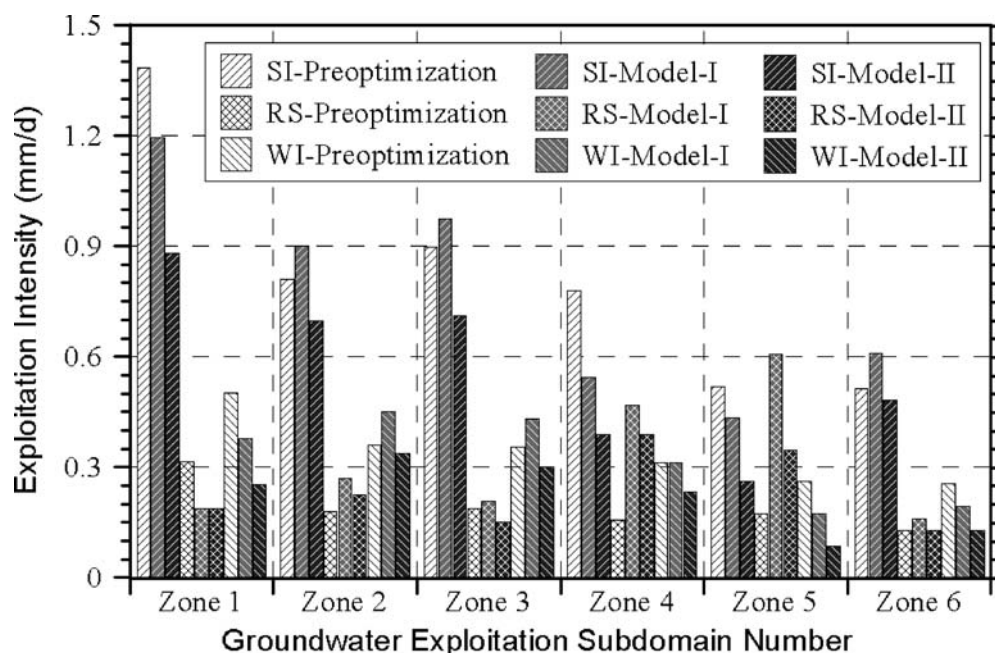


Fig. 6 The exploitation intensities obtained in all subdomains by the trial-and-error method and both model-I and model-II via GA optimization. *SI* stands for the spring irrigation period; *RS* for the rainy season and *WI* for the winter irrigation period. The term *preoptimization* represents the result based on the trial-and-error approach

similar between the trial-and-error results and the GA optimization results. Zone 1 has the greatest exploitation allocation, due to the excellent recharge conditions along the Yellow River bank (Fig. 5). Zone 4 has been assigned a very limited capacity for groundwater development, because large exploitation may reverse the existing groundwater flow direction there, which is needed for forming a hydraulic barrier to prevent groundwater contamination from Xiaoqing Stream. The seasonal variation of the optimal pumping rates corresponds well to the seasonal precipitation changes. The highest amount of irrigation is being suggested for the drought season and least for the rainy season. The total annual pumping rates given by model-I, model-II, and trial-and-error approach are 152.9, 112.6, and 142.2 million m³, respectively. Compared with trial-and-error results, model-I and model-II were able to increase and decrease the pumping amount respectively, while honoring all the constraints. Model-I was especially able to allocate greater exploitation amount to zones 2 and 3 via GA optimization. Model II, different from model-I and the previous trial-and-error work of Wu et al. (1998), aims at minimizing the groundwater exploitation while improving the environment by appropriately lowering the water table. Accordingly, the total amount of groundwater exploitation in Gaoqing Plain suggested by model-II is smaller than the solution given by either model-I or the trial-and-error method. Compared with model-I, however, model-II assigned almost comparable EIs or exploitation amounts to all zones via GA optimization during the rainy season to obey all the constraints on the upper bound of the water table. Figure 7a–c are the pre-rainy season water table distribution after 15 yrs of groundwater development based on strategies given by model-I, model II, and trial-and-error

approach, respectively. Compared with the initial water-table distribution (in masl) in Fig. 2a, the water table in Fig. 7a is reduced by about 2 m in most of the area at the end of the 15-yr management period. The decline in the water table, which is the direct result of pumping for irrigation, also reduces the amount of direct evaporation and the chance of soil salinization. The head distribution given by model-II in Fig. 7b is about 1 m higher than that in Fig. 7a. This is because model-I is a maximization problem, which requires the water table to approach the lower bound for hydraulic heads (H^{lower}). On the other hand, the model-II is a minimization problem, which requires the water table to approach the upper bound for hydraulic heads (H^{upper}). The water table distribution obtained by the trial-and-error approach (Wu et al. 1998) in Fig. 7c is also consistent with the results in Fig. 7a and b in terms of its general pattern. However, the surfaces of water tables in Fig. 7a and b are much smoother than that in Fig. 7c. This is because, in the GA S/O approach, the head constraints are strictly enforced automatically during the entire optimization process. The trial-and-error approach is, however, much more subjective, and its results may differ significantly depending on who is doing the operation. Furthermore, in Wu et al. (1998), the trial-and-error method took over 120 h to arrive at the result reported in Fig. 7c. In the current work, once the optimization problem is set up, the GA process takes less than 30 min to reach the optimal results. Therefore, the GA optimization approach is much more efficient and less subjective. For further illustration, Fig. 8a–c show the contours of the depth of the water table from ground surface as corresponding to the results in Fig. 7a–c. The comparison between Figs. 2b and 8a–c also leads to same conclusions.

Figure 9a and b shows the change of flow budget and water balance over time in the aquifer for model-I and model-II, respectively. At the current situation, the average annual evaporation is 158.1 million m^3 , accounting for 72.70% of the total annual outflow (217.47 million m^3) from the aquifer. When the maximum pumping strategy, as given by model-I, is employed, the artificial abstraction (152.9 million m^3) will become the biggest component of the total outflow; and the direct evaporation will gradually decrease over the 15-yr management period. For the first 5 yrs, the average annual amount of evaporation is 75.66 million m^3 , accounting for 34.79% of the total annual outflow; and for the following 10 yrs, the annual amount of evaporation is dramatically reduced to 29.56 million m^3 , accounting for only 13.59% of the total outflow from the aquifer. When the minimum pumping strategy is employed, the change of outflow terms observes a similar

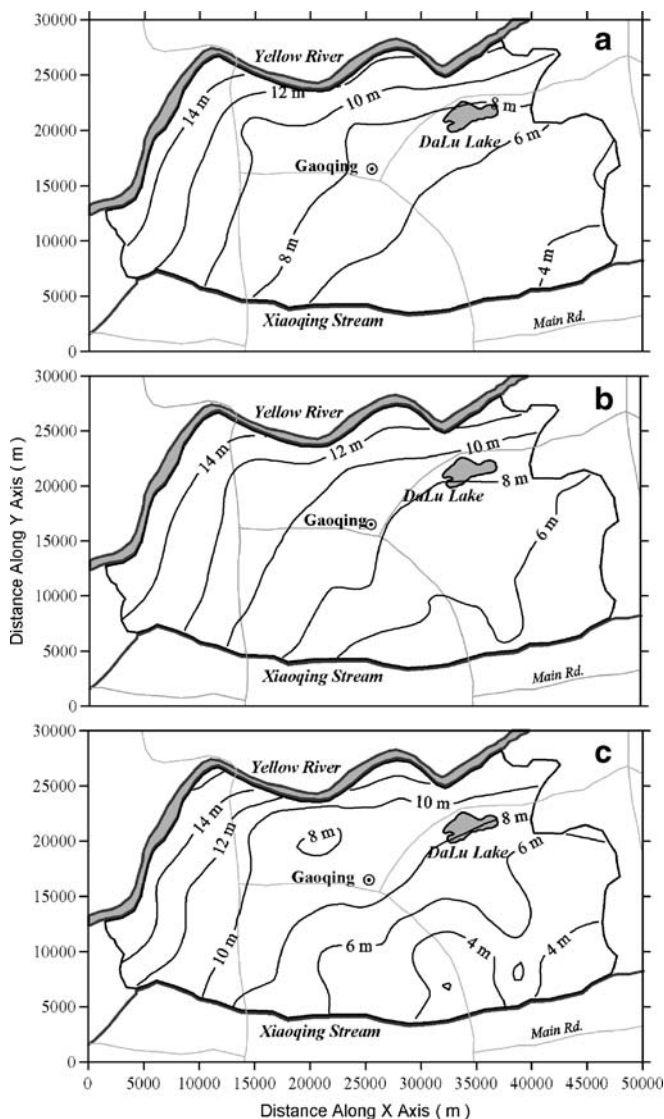


Fig. 7 The contours of the pre-rainy season water table (masl) distributions after 15 yrs of groundwater development based on strategies given by **a** model I, **b** model-II, and **c** the trial-and-error approach (modified from Wu et al. 1998)

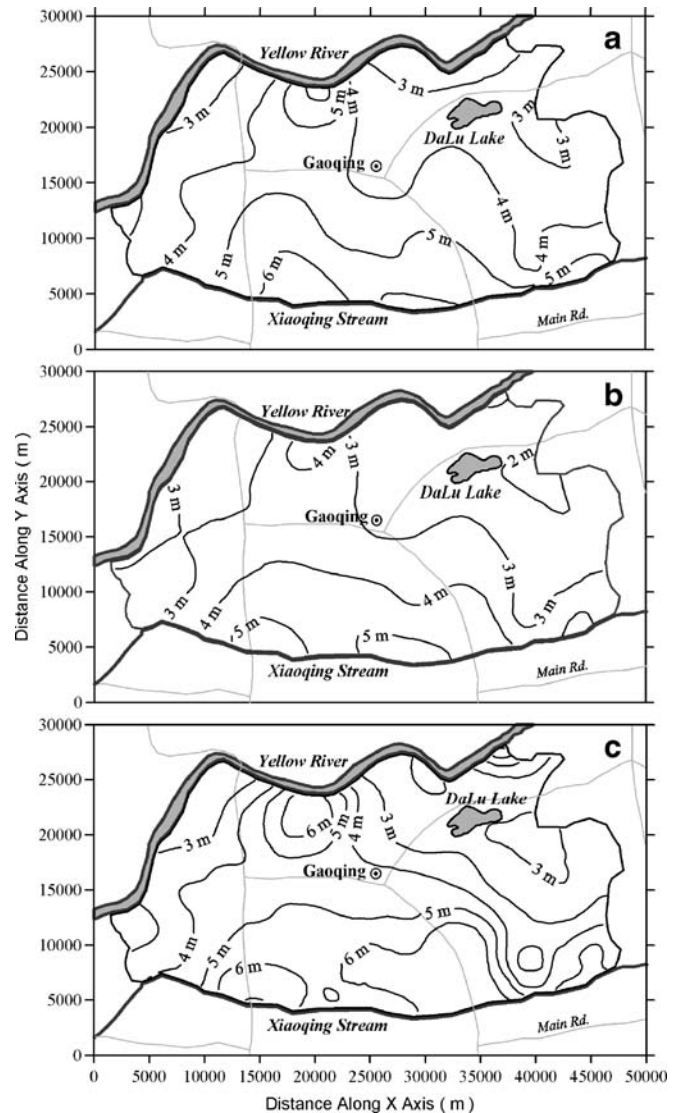


Fig. 8 Contours of the pre-rainy season depths to water table (meters below ground surface) after 15 yrs of groundwater development based on strategies given by **a** model-I, **b** model-II, and **c** the trial-and-error approach (modified from Wu et al. 1998)

trend with a smaller pumping (112.6 million m^3/yr) and a smaller reduction in direct evaporation as shown in Fig. 9b. The average annual discharge to the Xiaoqing Stream, in the amount of 0.6 million m^3 , is insignificant in comparison with the consumption of pumping and evaporation.

For both model-I and model-II, the inflow components are almost identical as illustrated in Fig. 9a and b and Table 2, since the irrigation amount has been fixed by supplementing water diverted from the Yellow River, regardless of the amount of groundwater pumping. The precipitation infiltration is the primary source of recharge for the unconfined aquifer, which can be up to 137.6 million m^3/yr , i.e., 63.28% of the total inflow, depending on the amount of precipitation. Also, the annual amounts of recharges via irrigation and lateral influx along the Yellow River are 43.20 and 16.21 million m^3 , accounting

for 19.86 and 7.45% of the total inflow, respectively. The storage change of the aquifer is to compensate the lowering of the water table. The bold line curves in Fig. 9a and b represent the aquifer storage budget changing over time. For the first 5 yrs, the value of the aquifer storage budget is always negative, showing that the water table is gradually lowered to an acceptable level. For the following 10 yrs, the annual values of the aquifer storage budget are mostly distributed between the interval $(-40, 40)$ million m^3 with a mean close to zero for both model-I and model-II, indicating that the water table has come to stabilize after 5 yrs of implementing the proposed groundwater development strategies. Table 2 clearly shows the change of flow budget and water balance over time during the entire 15-yr management period for both model-I and model-II.

The optimal results from model-I and model-II supply an upper (152.9 million m^3) and lower limit (112.6 million m^3) on the annual pumping amount while satisfying all the environmental constraints. In practice, the administrators or municipal authorities will balance the trade-off between the low cost for diverting surface water and the pressure for conserving the Yellow River water, and decide the intensity of groundwater exploitation from these limits. Given that the maximum water diversion from the Yellow River is 180 million m^3/yr under current regulations and the present local water demand is 200 million m^3 , the possible water intake structure can be graphically depicted

as shown in Fig. 10, where the X-axis represents the annual diversion amount of the Yellow River water and the Y-axis represents the annual abstraction of the groundwater. With the optimal groundwater pumping ranging from 112.6 to 152.9 million m^3 , the corresponding annual diversion of the Yellow River water should be ranging from 87.4 to 47.1 million m^3 in order to meet the current water demand. When there is more than 87.4 million m^3 of surface water available, the total water supply potential will surpass the local water demand. The shaded region as defined by P_{a1} , P_{a2} , P_{a3} , and P_{a4} in Fig. 10 gives the feasible water intake options. As the water demand increases, the water demand line will move toward the right as indicated by the dashed line in Fig. 10, which will reduce the feasible water intake region. Under current regulation of a maximum water diversion of 180 million m^3 , the water supply capacity in this region is $152.9 + 180 = 332.9$ million m^3 , which is located at the vertex point P_{a4} . Note that the simple straight-line presentation in Fig. 10 requires the assumption of the annual irrigation amount staying constant even when the total water demand increases. However, as we have seen in previous analyses, the majority of recharge comes from the precipitation infiltration, and the variation in irrigation amount produces insignificant changes in recharge; therefore, the straight-line graphical presentation will remain a useful tool for guiding the water supply management.

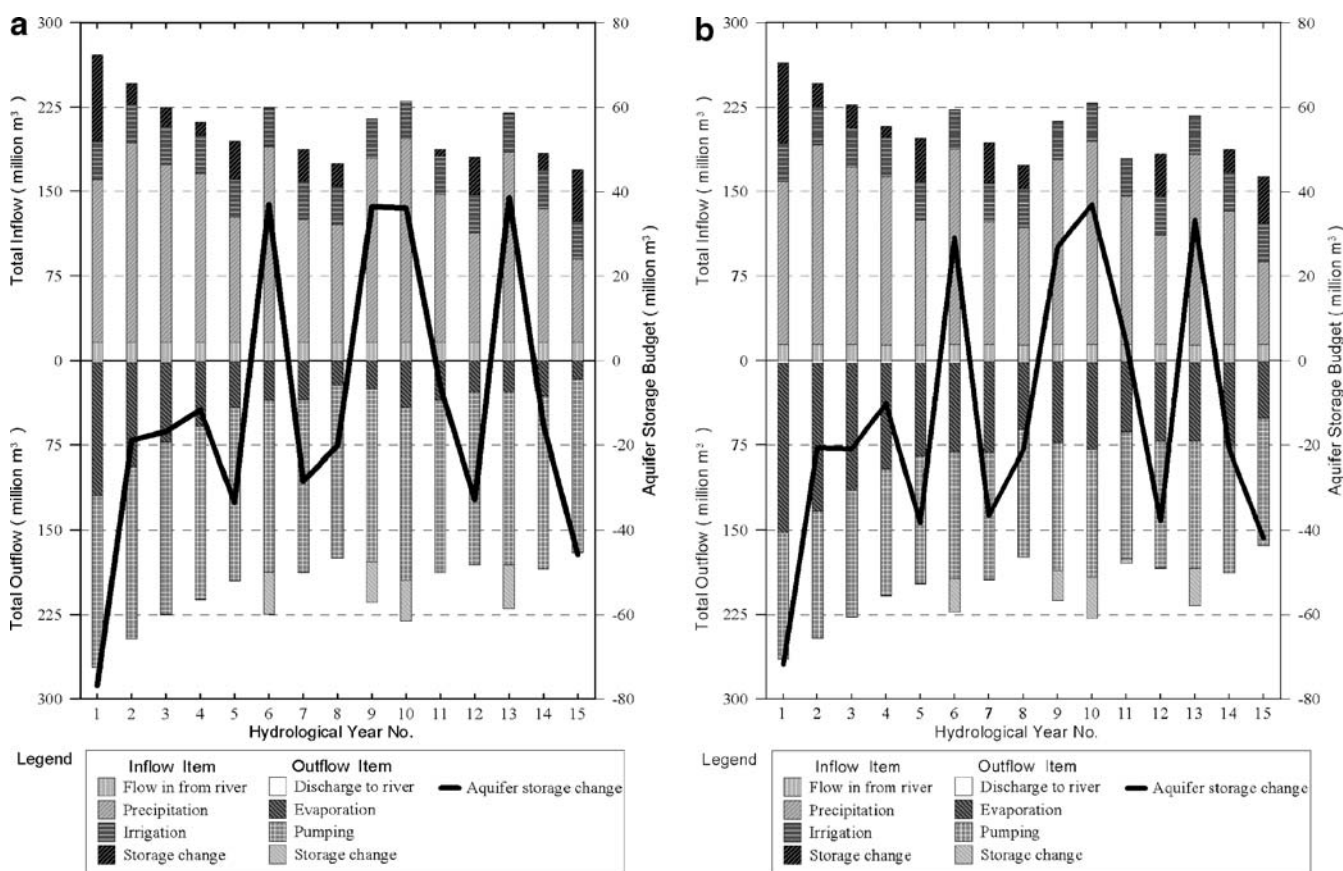


Fig. 9 The change of flow budget and water balance over time during the 15-yr management period for a model-I and b model-II

Table 2 The flow budget and water balance showing the change of inflow and outflow items over time during the 15-yr management period for both model-I and model-II (unit of measure is million m³)

Items	Time ^a	Inflow item ^b (5)=(1)+(2)+(3)+(4)					Outflow item ^c (10)=(6)+(7)+(8)+(9)					Aquifer storage change (11)=(9)-(4)
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	
Model-I	1	16.21	144.74	34.22	76.82	271.99	1.50	117.44	152.90	0.15	271.99	-76.67
	2	16.21	177.24	34.19	18.91	246.55	1.40	92.11	152.90	0.14	246.55	-18.77
	3	16.21	157.87	34.19	16.85	225.11	1.48	70.49	152.90	0.24	225.11	-16.61
	4	16.21	149.79	34.21	11.67	211.89	1.20	57.38	152.90	0.41	211.89	-11.26
	5	16.21	111.15	34.18	33.44	194.98	1.00	40.87	152.90	0.21	194.98	-33.23
	6	16.21	174.17	34.21	0.20	224.79	0.80	34.07	152.90	37.02	224.79	36.82
	7	16.21	109.03	34.20	28.49	187.93	0.10	34.60	152.90	0.33	187.93	-28.16
	8	16.21	104.69	34.20	20.03	175.14	0.40	21.73	152.90	0.11	175.14	-19.92
	9	16.21	164.14	34.20	0.12	214.67	0.10	25.15	152.90	36.52	214.67	36.40
	10	16.21	180.18	34.19	0.21	230.79	0.15	41.59	152.90	36.15	230.79	35.94
	11	16.21	131.37	34.20	6.30	188.08	0.02	35.10	152.90	0.06	188.08	-6.24
	12	16.21	97.60	34.21	32.89	180.90	0.10	27.75	152.90	0.15	180.90	-32.74
	13	16.21	169.20	34.18	0.14	219.73	0.40	27.87	152.90	38.55	219.73	38.41
	14	16.21	118.96	34.22	15.28	184.66	0.25	31.41	152.90	0.10	184.66	-15.18
	15	16.21	73.72	34.20	45.65	169.78	0.10	16.38	152.90	0.40	169.78	-45.25
Model-II	1	14.16	144.74	34.22	71.68	264.81	2.55	149.66	112.60	0.15	264.96	-71.53
	2	14.03	177.24	34.19	20.64	246.10	2.60	130.91	112.60	0.14	246.24	-20.50
	3	14.08	157.87	34.19	20.88	227.02	2.64	111.78	112.60	0.24	227.26	-20.64
	4	13.88	149.79	34.21	10.22	208.11	2.55	92.96	112.60	0.41	208.52	-9.81
	5	13.88	111.15	34.18	38.24	197.45	2.25	82.60	112.60	0.21	197.66	-38.03
	6	14.14	174.17	34.21	0.29	222.81	1.93	78.83	112.60	29.16	222.52	28.87
	7	14.08	109.03	34.20	36.49	193.80	1.31	79.89	112.60	0.33	194.13	-36.16
	8	13.83	104.69	34.20	21.18	173.91	1.56	59.74	112.60	0.11	174.02	-21.07
	9	14.03	164.14	34.20	0.27	212.64	1.31	71.46	112.60	27.01	212.37	26.74
	10	14.19	180.18	34.19	0.36	228.92	1.45	77.59	112.60	36.92	228.56	36.56
	11	14.20	131.37	34.20	0.01	179.78	1.39	61.52	112.60	4.26	179.77	4.25
	12	14.19	97.60	34.21	37.76	183.75	1.47	69.68	112.60	0.15	183.90	-37.61
	13	13.88	169.20	34.18	0.32	217.58	1.57	69.78	112.60	33.31	217.26	32.99
	14	13.94	118.96	34.22	20.90	188.02	1.46	73.96	112.60	0.20	188.22	-20.70
	15	13.98	73.72	34.20	41.80	163.70	1.36	49.74	112.60	0.17	163.87	-41.63

^a Hydrological year number for the entire 15-yr management period

^b Items (1)–(5) are the inflow items of water budget in each hydrological year, representing flow in from river, precipitation, irrigation, storage change, and the total inflow, respectively

^c Items (6)–(10) are the outflow items of water budget in each hydrological year, representing discharge to river, evaporation, pumping, storage change, and the total outflow, respectively

If the water available for diversion in the Yellow River is less than 47.1 million m³/yr, as have been the many cases when the Yellow River has experienced cutoffs since 1972, there will not be enough water produced in

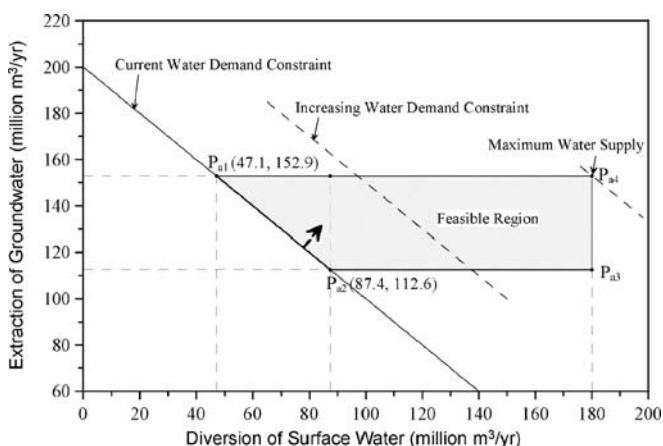


Fig. 10 The possible water intake structure under the proposed optimal groundwater development strategies. The shaded region as defined by P_{a1} , P_{a2} , P_{a3} , and P_{a4} gives the feasible water intake options

Gaoqing Plain to meet all water needs while satisfying all environmental constraints and administrative regulations. Under such circumstances, there are only two alternatives. Either the total water demand will need to be reduced through adopting various water saving measures in both agricultural and industrial sectors, or the water supply will need to be increased by tapping into other water sources. The “South–North Water Transfer Project”, currently under construction in China, is one of such efforts to increase the water supply, which, once accomplished, will alleviate the water stress in the northern region by taking water from Yangtze River basin in the south.

Summary and recommendations

In the past several decades, the diversion of the Yellow River water for intensive irrigation in Gaoqing Plain has produced high agricultural yields and economic income, along with some undesirable environmental consequences. The infiltration of irrigation water has caused the water table to rise and has increased evaporation, which has lead to soil salinization. The

heavy use of irrigation water from the Yellow River also brought in much sandy silt to local farmland. The accumulation of sandy silt has reduced the area of productive farmland and caused other environmental problems. In recent years, the Yellow River has experienced frequent cut-offs due to excessive diversion and consumption along its reaches. To sustain the agricultural outputs and local economy, municipal authorities have to look for water from somewhere else such as the local aquifers. In the current study, optimization models are coupled with a groundwater flow simulator to search for the best groundwater exploitation strategy. A genetic algorithm is used to determine the maximum and minimum groundwater pumping strategies that can satisfy various environmental constraints.

The optimization results show that the Gaoqing Plain aquifer has great potential for supplying water to meet the local needs. The proposed groundwater development strategies can capture most of the nonbeneficial evaporation for local water supply. Compared with the trial-and-error method (Wu et al. 1998), the GA based simulation-optimization approach adopted here is more effective and efficient, and less prone to human subjectivity in the search for optimal solutions.

The implementation of the proposed groundwater development strategies will lower the water table and stabilize it at an appropriate level, thus minimizing the risks for several adverse environmental impacts, including soil salinization, land subsidence and groundwater contamination. The allowable groundwater exploitation amount, however, is not sufficient to meet the total water demand of this area. Even if the allowable groundwater exploitation is maximized, i.e., 152.9 million m³/yr, Gaoqing Plain still needs at least 47.1 million m³ of water diverted from the Yellow River in order to balance the water need. If the annual Yellow River water available for diversion is less than 47.1 million m³, the water supply will not be enough for meeting the needs. The Gaoqing Plain will have to explore measures to reduce its water demand (e.g., changing its agricultural structure and adopting water-saving crops etc.) or increase its water supply via other sources (e.g., inter-basin water transfer).

When using the results of the current study in managing the local water resources, the managers should be aware of the possible impacts of uncertainties in future climate changes. In the current study, the optimal groundwater development strategies were devised based on the assumption that the future climatic conditions will follow a similar trend as recorded in the existing weather data. If the climate in the next 15 yrs changes to a wetter or drier condition, there will be, accordingly, more or less recharge to the aquifer resulting from the precipitation infiltration. The optimal solutions should, accordingly, then have higher or lower pumping rates than those given in the current study. For example, when one sets the average monthly precipitation of 1956–2002 as the input data (annual precipitation of 579.5 mm) for the

future 15-yr management period in this study, the total annual pumping rates given by model-I and model-II via GA optimization become 184.7 and 135.3 million m³, respectively.

In summary, the most significant contribution of the current study is to support the change of the water resources development strategy in Gaoqing Plain from mainly diverting the Yellow River water to combining a proper exploitation of local groundwater and necessary diversion of the Yellow River water. This new strategy will not only help to ease the existing pressure on surface water supply due to recent cut-offs in the Yellow River flow, but also provide a good buffer for meeting possible future water-demand increase and sustaining further economic development in Gaoqing Plain. It will also leave more water for the downstream users and help reduce the chances of conflict. In addition, the planned development of the groundwater resource will produce many environmental benefits, including the alleviation of soil salinization, the reduction of silt accumulation, and the protection of groundwater quality etc.

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