A large-scale conjunctive management model of water resources for an arid irrigation district in China

Weifeng Yue and Chesheng Zhan

ABSTRACT

The quantity of available water resources has been recognized as the key limiting factor for development of most of the arid regions. This paper focuses on the simulation–optimization for conjunctive use of surface water and groundwater on a large scale. In this study, Hetao Irrigation District in China, one of the largest irrigation districts in the Yellow River basin, is selected as a representative study area. The conjunctive management model of water resources is developed by means of dynamically coupling a large-scale hydrological model with an optimal allocation model. A groundwater level is adopted in the coupled model as the constraint condition and the optimal conjunctive utilization quantity of surface water and groundwater is set as the objective function. Finally, the coupled model is applied to calculate the optimal water supply quantity of surface water and groundwater and sustainable utilization scheme of water resources for 2020 and 2030 in Hetao Irrigation District. The modeling results demonstrate the conjunctive management model of water resources is an effective tool for appraising water resources in large-scale arid regions.

Key words | arid irrigation district, conjunctive use, groundwater, large scale, surface water

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INTRODUCTION

Hetao Irrigation District, located in Inner Mongolia and the upper reaches of the Yellow River in China, is one of the three largest irrigation districts throughout the entire country (Figure 1). The irrigated area is about 5.74×10^3 km^2, which accounts for 56.2% of the total land area. It is divided into five irrigation subdistricts as shown in Figure 1. The irrigation water use is primarily diverted from the Yellow River, while the groundwater is the main source for domestic and industrial water use. The area has a typical arid and semi-arid continental monsoon climate. High evapotranspiration and low precipitation influence the recharge and discharge of groundwater, and its salinity. Therefore, irrigation plays an important role in Hetao Irrigation District.

The average annual irrigation water is 5.18×10^9 m^3, but the irrigation efficiency is approximately 0.33. In addition, due to severe water scarcity in the Yellow River basin, the amount of irrigation water drawn from the Yellow River will be limited to less than 4.0×10^9 m^3 per year in the future according to the water resources management data issued by the Yellow River Conservancy Commission. However, the natural environment of the upstream area in the Yellow River basin is degraded and the water resources are scanty, which promotes conflict with the increasing water demand. How to increase the efficiency of water use to maintain sustainable development of the research area is the key issue faced by the local authority. On the other hand, unreasonable use of groundwater increases the risk of the quality of degradation resulting from low groundwater level and the threat of salinization resulting from a high level, which may worsen agriculture development and land exploitation in this region (Wang *et al.* 1993). Therefore, using groundwater efficiently becomes more and more important as well as controlling the groundwater table, especially in arid and semi-arid regions.

Conjunctive use of surface and groundwater is one of the most effective water management approaches for dealing with increasing water demand and inadequate surface supplies. Many attempts have been made by different researchers to study optimal allocation of land, water, and

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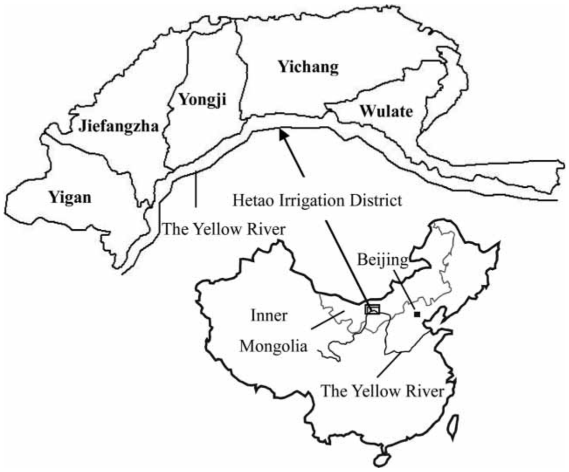

Figure 1 | Schematic layout of Hetao Irrigation District in China.

other resources for various uses. System approaches and their framework of mathematical models have long been used in analyzing conjunctive water use. Several modeling approaches, such as linear and nonlinear programming, dynamic programming, simulation, hierarchical multilevel optimization, and combined optimization–simulation have been reported in the literature (Buras 1963; Aron 1969; Aron & Scott 1971; Young & Bredehoeft 1972; Haimes & Dreizen 1977; O'Mara & Duloy 1984; Willis *et al.* 1989; Onta *et al.* 1991; Matsukawa *et al.* 1992; Reichard 1995; Watkins & McKinney 1998; Azaiez & Hariga 2001; Rao *et al.* 2004; Syaukt & Fox 2004; Yang *et al.* 2009; Safavi *et al.* 2010). Peralta *et al.* (1995) developed a linear programming-based simulation come optimization model to obtain sustainable groundwater extractions over a period of five decades, in a conjunctive water use scenario. Belaineh *et al.* (1999) presented a simulation–optimization model that integrates linear reservoir decision rules, detailed simulations of stream/aquifer system flows, conjunctive use of surface and groundwater, and delivery to water users via branching canals. Groundwater flow was simulated using the MODFLOW program, which solves the quasi three-dimensional groundwater flow equations. Vedula *et al.* (2005) developed a mathematical model to arrive at an optimal conjunctive use policy for irrigation of multiple crops in a reservoir–canal–aquifer system. In their studies, the conjunctive use model is formulated with several constraints linked together by appropriate additional constraints as a deterministic linear programming model. The aquifer response is modeled through the use of a finite element groundwater model. Khare *et al.* (2006) presented a simple economic-engineering optimization model, to explore the possibilities of conjunctive use of surface and groundwater using linear programming with various hydrological and management constraints, and to get an optimal cropping pattern for optimal use of water resources for maximization of net benefits. Bharati *et al.* (2008) described the development, calibration, and preliminary application of a dynamically coupled economic-hydrologic simulation–optimization model ensemble designed to evaluate the conjunctive use of surface and groundwater in small reservoir-based irrigation systems characteristic of the Upper Volta basin. The model ensemble consists of the physical hydrology model WaSiM-ETH and an economic optimization model written in GAMS.

It is complex to incorporate a simulation model with an optimization-based management model. Embedding technique and response matrix approach are the two methods generally used to incorporate a flow model with a management model (Buras 1963; Bredehoeft & Young 1970, 1983; Dreizin & Haimes 1977; Willis & Yeh 1987; Hakan *et al.* 1999; Karamouz *et al.* 2004). Because of the complexity and nonlinearity of systems, flow models are often simplified and embedded in optimal models. Groundwater movement may not be simulated accurately with such a simplified model, especially for large-scale areas.

The primary objective of this study is to develop a conjunctive management model of surface and groundwater, and to couple a large-scale flow model with an optimal allocation model. This paper first discusses the characteristics and current use of water resources in the irrigation district. Then, a large-scale groundwater flow model is developed based on the field observation data. In addition, an optimization model is formulated. Finally, optimal strategy of conjunctive use of surface and groundwater is analyzed by dynamically coupling the simulation model with the optimization model.

SITE DESCRIPTION

Climate

The average annual rainfall and evaporation in the Hetao Irrigation District is about 160 and 2,240 mm, respectively, from 1981 to 2009. However, rainfall is highly variable with annual totals ranging from 70 to 250 mm. In addition to having a highly variable inter-annual rainfall, Hetao Irrigation District exhibits a strongly seasonal trend. Two-thirds of the rain occurs between June and September (Figure 2). Generally, there are significant diurnal temperature fluctuations in Hetao Irrigation District. According to the daily air temperature of the research area from 1981 to 2009, the extreme high temperature is 38 °C, and the extreme low temperature is −35.3 °C. Seasonal temperatures range from an average of −7.6 °C in the winter, to 22.7 °C in the summer. Mean monthly air temperatures are shown in Figure 2.

Water resources

Water from the Yellow River is the major source for irrigation in Hetao Irrigation District. The annual inlet of Yellow River water consumed by only agriculture ranges from 3.2 to 5.3 billion m^3 depending on the actual irrigated area (average 990 mm/a).

The study area is located at a river alluvial plain with a very gentle slope of 1/10,000. The area is an interior down-faulted basin which has a small groundwater hydraulic gradient of 1/4,000–1/10,000. Groundwater in this region mainly moves in a vertical direction affected by the infiltration, evaporation, and extraction. According to multi-year statistical data of groundwater use, the annual average groundwater supply is 7.61×10^8 m^3, but consumption is only 1.48×10^8 m^3, accounting for 19.5% of groundwater supply and 3% of total water consumption. Table 1 shows the annual average amount of groundwater consumption for agriculture, industry, and domestic use in the five zones, respectively.

Despite the intensive and long-term irrigation, the average depth of groundwater remains relatively stable and varies from 0.5 m in November to 3.0 m in February (Wu 2009). The annual average depth of the groundwater table shows the same trend as the amount of irrigation water (Figure 3).

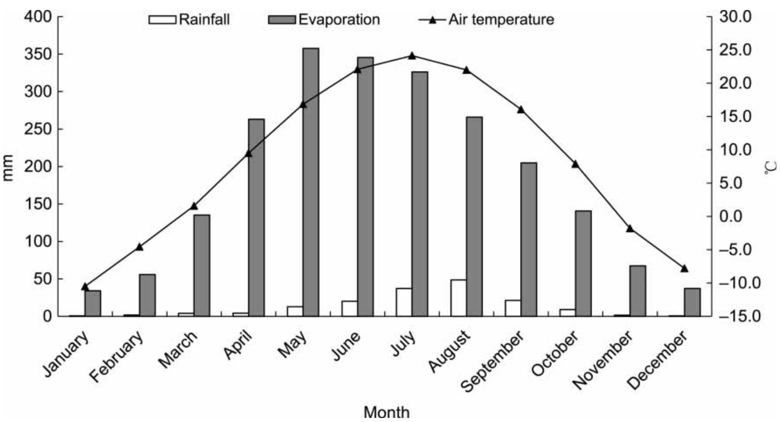

Figure 2 | Average monthly rainfall, evaporation, and air temperature recorded in Hetao Irrigation District (29 years of data).

Table 1 | Annual average amount of groundwater use in Hetao Irrigation District

Zone	Groundwater supply (10^8 m^3)	Agricultural water (10^8 m^3)	Agricultural water (%)	Industrial water (10^8 m^3)	Industrial water (%)	Domestic water (10^8 m^3)	Domestic water (%)	Groundwater use efficiency (%)
Yigan	1.595	0.084	5.3	0.043	2.7	0.058	3.7	11.7
Jiefangzha	1.363	0.063	4.6	0.062	4.6	0.146	10.7	19.9
Yongji	1.650	0.119	7.2	0.202	12.3	0.236	14.3	33.8
Yichang	2.218	0.092	4.1	0.050	2.2	0.140	6.3	12.7
Wulate	0.782	0.118	15.1	0.032	4.1	0.035	4.5	23.7
Total	7.609	0.476	6.3	0.390	5.1	0.616	8.1	19.5

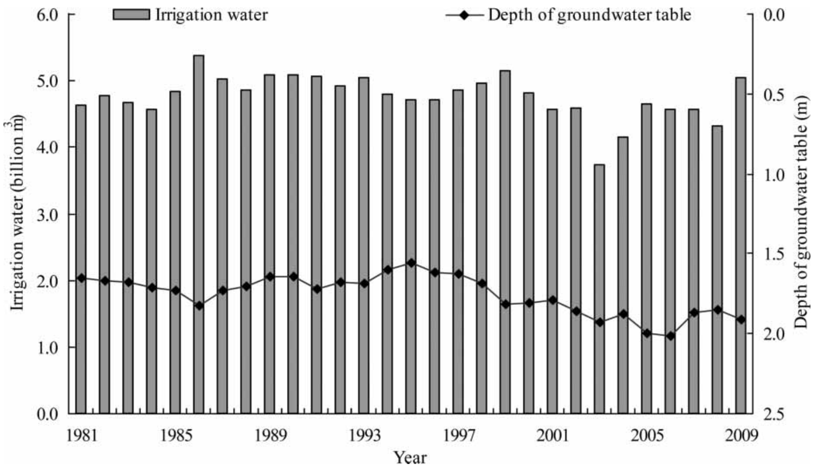

Figure 3 | Variable trend of irrigation water and average annual depth to groundwater.

MATERIALS AND METHODS

In this paper, a large-scale conjunctive management model of water resources is developed by means of dynamically coupling a large-scale hydrological model with an optimal allocation model.

Optimization allocation model

Variables setting

At present, Hetao Irrigation District is mainly irrigated by surface water, and the groundwater is mostly used for domestic use and industry. With the rapid economic development and population growth, water demand will increase sharply. Thus, the well–canal combined irrigation area needs to be expanded to make the most use of the groundwater. At the same time, in order to prevent decline of the groundwater table resulting from centralized exploitation, surface water can also be supplied for domestic use and to industry. Thus, a schematic diagram of the conjunctive use system is presented as shown in Figure 4. The system is characterized by three main components: the surface water supply system, the water use system, and the underlying aquifer with the associated dynamic relationships defining the interactions among them (Li *et al.* 1999; Qi *et al.* 2004; Bharati *et al.* 2008). In order to reduce the surface water use from $5.18 \times 10^9\ m^3$ of the present year to $4.0 \times 10^9\ m^3$ of the planning year gradually, an interim period should be provided. Hence, the years 2020 and 2030 have been set as the planning years according to local government water resource planning (Yang *et al.* 2005). The main differences between 2020 and 2030 are the basic water requirements for irrigation, industry, and domestic use. A 1-year period of water resources planning has been considered with monthly planning periods.

As the surface water from the Yellow River will be limited to less than $4.0 \times 10^9\ m^3$ by the management institution, the purpose of the optimal allocation model is to improve the groundwater use efficiency, and to minimize the surface water supply. Thus, the objective function used for the overall conjunctive use model is:

$$\min Z = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} (\mathrm{XSW}_{i,j,t} - \mathrm{XGW}_{i,j,t}) \quad (1)$$

where i is the number of irrigation subdistricts in the study area ($i = 1, 2, \ldots, 5$, representing Yigan, Jiefangzha, Yongji, Yichang, and Wulate, respectively), j is the number of water use sectors ($j = 1, 2, \ldots, 4$, representing agricultural water, industrial water, urban domestic water, and rural domestic water, respectively), t is the number of months ($t = 1, 2, \ldots, 12$), $\mathrm{XSW}_{i,j,t}$ represents the surface water allocation for jth water use sector in ith irrigation subdistrict during tth time interval [L^3], $\mathrm{XGW}_{i,j,t}$ represents the groundwater allocation for jth water use sector in ith irrigation subdistrict during tth time interval [L^3].

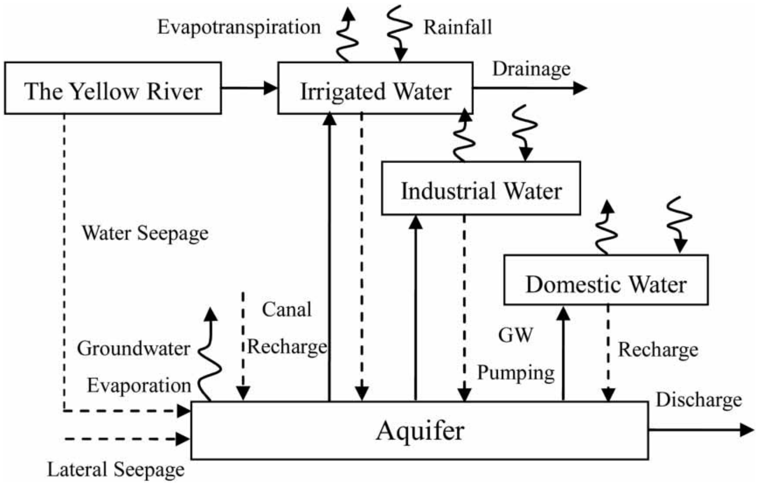

Figure 4 | Schematic diagram of the conjunctive use system.

Constraint conditions

Equation (1) is to be minimized subject to a variety of constraints.

1. Water supply constraints: Monthly surface water allocation in each subdistrict cannot exceed the availability of water from the Yellow River. This constraint can be expressed as:

$$\mathrm{XSW}_{i,j,t} \leq \mathrm{SW}_{i,j,t}$$
$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\mathrm{SW}_{i,j,t} \leq \mathrm{TSW} \tag{2}$$

where $\mathrm{SW}_{i,j,t}$ is the surface water available for jth water use sector in ith irrigation subdistrict for tth time interval [L^3], TSW is the total annual surface water available at the entrance of the canal [L^3].

The annual total water pumped from the groundwater of the study area should not exceed the annual recharge. Thus the constraints on groundwater availability for all the subdistricts of the study area can be expressed as:

$$\mathrm{XGW}_{i,j,t} \leq \mathrm{GW}_{i,j,t}$$
$$\sum_{j=1}^{J}\sum_{t=1}^{T}\mathrm{GW}_{i,j,t} \leq C_i \times \mathrm{TGW}_i \tag{3}$$

where $\mathrm{GW}_{i,j,t}$ is the groundwater available for jth water use sector in ith irrigation subdistrict for tth time period [L^3], C_i is the permissible mining allowance in ith irrigation subdistrict, and TGW_i is the annual groundwater recharge in ith irrigation subdistrict [L^3].

2. Water requirement constraints: The total monthly water requirement for all the water use sectors in each irrigation subdistrict should be met with the surface and groundwater allocations. Therefore, constraints for water requirement can be expressed as:

$$\mathrm{XGW}_{i,j,t} + \mathrm{XSW}_{i,j,t} \geq \mathrm{TWR}_{i,j,t} \tag{4}$$

where $\mathrm{TWR}_{i,j,t}$ is the water requirement of jth water use sector in ith irrigation subdistrict for tth time period [L^3].

3. Groundwater level constraints: To prevent salinization or desertification resulting from rise or decline of groundwater level, a reasonable range of groundwater level of the irrigated area should be maintained. In addition, to avoid extension of the groundwater depression cones resulting from centralized exploitation, the groundwater level at the boundaries of industrial and domestic water use sectors should be controlled within a rational range. Thus, the control equation can be formulated as:

$$\begin{aligned} &\left|H_{i,j,t} - H_{r1}\right| \leq \varepsilon \quad j = 1 \\ &\left|HB_{i,j,t} - H_{r2}\right| \leq \varepsilon \; j = 2, 3, 4 \end{aligned} \tag{5}$$

where $H_{i,j,t}$ is the groundwater level of jth water use sector in ith irrigation subdistrict for tth time period [L], $HB_{i,j,t}$ is the groundwater level of boundaries of jth water use sector in ith irrigation subdistrict for tth time period [L], H_{r1} and H_{r2} are the optimum groundwater levels of irrigated and non-irrigated areas, respectively [L], ε is the controlling precision.

In addition, canal capacity constraints, well capacity constraints, and non-negative constraints have been considered.

Large-scale groundwater model

Formulation

The following assumptions are made for the groundwater conceptual model:

1. Flow in the aquifer can be approximated as a two-dimensional flow.
2. Darcy's law and Dupuit's assumption are valid.
3. The aquifer is unconfined, heterogeneous, isotropic and bounded at the bottom by an impervious layer.
4. The saturated thickness of the aquifer is always large compared to the drawdown; thus the aquifer transmissivity is independent of the head.

The governing equations for the two-dimensional, unsteady flow in the isotropic, heterogeneous, unconfined aquifer can be expressed as:

$$\begin{cases} \frac{\partial}{\partial x}\left(T\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial H}{\partial y}\right)+\omega=\mu\frac{\partial H}{\partial t} & (x,y)\in\Omega,\ t\geq 0 \\ H(x,y,0)=H_0(x,y) & (x,y)\in\Omega,\ t=0 \\ T\frac{\partial H}{\partial n}=\begin{cases}0 \\ q\end{cases} & \begin{matrix}(x,y)\in\Gamma_{2-1},\ t\geq 0 \\ (x,y)\in\Gamma_{2-2},\ t\geq 0\end{matrix} \\ H(x,y,t)=H_1(x,y) & (x,y)\in\Gamma_1,\ t\geq 0 \\ \omega=W(x,y,t)-E(x,y,t)-\sum_{i=1}^{N_w}Q_i(x_i,y_i,t) & \end{cases} \tag{6}$$

where T is the transmissivity [L^2T^{-1}], H is the groundwater level [L], H_0 is the initial groundwater level [L], μ is the specific yield, W is the summation of recharge rate per unit area [LT^{-1}], including rainfall infiltration, canal seepage, irrigation infiltration, and well irrigation return, E is the groundwater evaporation rate per unit area [LT^{-1}], Q_i is the pumping rate per unit area [LT^{-1}], x and y are the Cartesian coordinates in plan, and t is the time in days.

The finite element formulation based on the Galarkin weighted residual method is applied to Equation (6). The model was designed for some specific flow conditions, such as irregular boundary, temporal and spatial variation of rainfall infiltration and evaporation. In addition, the model can be easily coupled with an optimal model.

Sub-areas and boundary conditions

According to the types of land use and different hydrogeological units, the study area is divided into several sub-areas. Furthermore, based on the actual groundwater flow conditions in Hetao Irrigation District, three boundary conditions are specified, including Dirichlet boundary B_h, Neumann boundary B_q, and Impermeable boundary B_0. The Neumann boundary B_q includes both the lateral seepage from mountains B_{q1} and from the Yellow River B_{q2} (Figure 5).

Evaporation

The soil water dynamics experience three different periods each year, a freezing period, thawing period, and irrigation period, according to the observed climatic data in the study area. Different periods have different mechanisms of evaporation. Groundwater evaporation for the three periods is simulated with field observed data from 1981 to 2009.

1. Evaporation during the irrigation period: The relationship between the evaporation coefficient and depth of the groundwater table in Hetao Irrigation District is analyzed based on the field experimental data. Figure 6 shows the results.

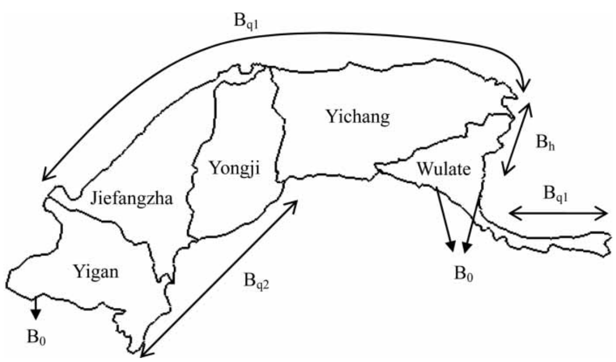

Figure 5 | Schematic diagram of sub-areas and boundary conditions.

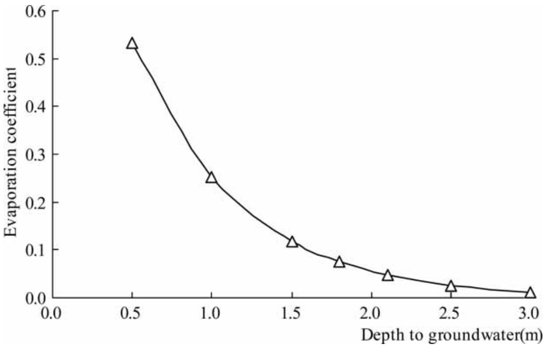

Figure 6 | Relationship between the evaporation coefficient and depth to groundwater.

Groundwater evaporation during the irrigation period can be evaluated with the following equation:

$$E_{i,j} = F_{i,j} \cdot \varepsilon_0 \cdot C_{i,j} \tag{7}$$

where $E_{i,j}$ is the groundwater evaporation of irrigation period for jth water use sector in ith irrigation subdistrict [L^3], $F_{i,j}$ is the area of jth water use sector in ith irrigation subdistrict [L^2], ε_0 is the pan evaporation [L], and $C_{i,j}$ is the evaporation coefficient of groundwater jth water use sector in ith irrigation subdistrict.

2. Evaporation during the freezing and thawing periods: According to the observed and experimental results, water is transferred from the lower floor with high temperature to the frozen floor with low temperature due to the temperature gradient in the freezing period, which results in the decline of the groundwater table. In contrast, water moves from the higher floor to the lower floor in the thawing period, leading to an increase of the groundwater table. In other words, evaporation of freezing and thawing periods causes a water cycle between the soil water and groundwater. Evaporation of freezing and thawing periods can be calculated by the following methods.

First, estimate the groundwater evaporation of freezing and thawing periods with the balance model using long-term observed data of rainfall, pan evaporation, irrigation and drainage water, depth to groundwater, etc. Second, analyze the relationship between evaporation and depth of the groundwater table, and verify their calculating equations. Then, calculate the groundwater evaporation with the observed groundwater depth using the equations.

Figure 7 shows the relationship between evaporation and depth to groundwater in freezing and thawing periods.

Infiltration

Rainfall infiltration, canal seepage, irrigation infiltration, and well irrigation return can be evaluated with the following equations:

$$\mathrm{RI}_{i,j,t} = P_{i,j,t} \cdot \alpha_{i,j} \tag{8}$$

$$\mathrm{CWS}_{i,1,t} = \frac{\mathrm{XSW}_{i,1,t} \cdot \beta_i}{F_{i,1}} \tag{9}$$

$$\mathrm{IWI}_{i,1,t} = \frac{\mathrm{XSW}_{i,1,t} \cdot \eta_i \cdot \gamma_i}{F_{i,1}} \tag{10}$$

$$\mathrm{WIR}_{i,1,t} = \frac{\mathrm{XGW}_{i,1,t} \cdot \theta_i}{F_{i,1}} \tag{11}$$

where $\mathrm{RI}_{i,j,t}$ is the rainfall infiltration for jth water use sector in ith irrigation subdistrict for tth time period [L], $P_{i,j,t}$ is the precipitation for jth water use sector in ith irrigation subdistrict for tth time period [L], $\alpha_{i,j}$ is the recharge coefficient of rainfall infiltration for jth water use sector in ith irrigation subdistrict, $\mathrm{CWS}_{i,1,t}$, $\mathrm{IWI}_{i,1,t}$, and $\mathrm{WIR}_{i,1,t}$, are the canal seepage, irrigation infiltration, and well irrigation return for agricultural water use sector in ith irrigation subdistrict for tth time period, respectively [L], η_i is the water efficiency of the canal system, β_i, γ_i and θ_i are the recharge coefficients of canal seepage, irrigation infiltration, and well irrigation return for ith irrigation subdistrict.

These recharge coefficients, shown in Table 2, are evaluated or calculated using long-term field observed data.

Parameter calibration

As the most important hydrogeological parameters of the groundwater flow model, the specific yield μ and the hydraulic conductivity K are calibrated based on the field observation data from 1990 to 1999. The results are shown in Table 2.

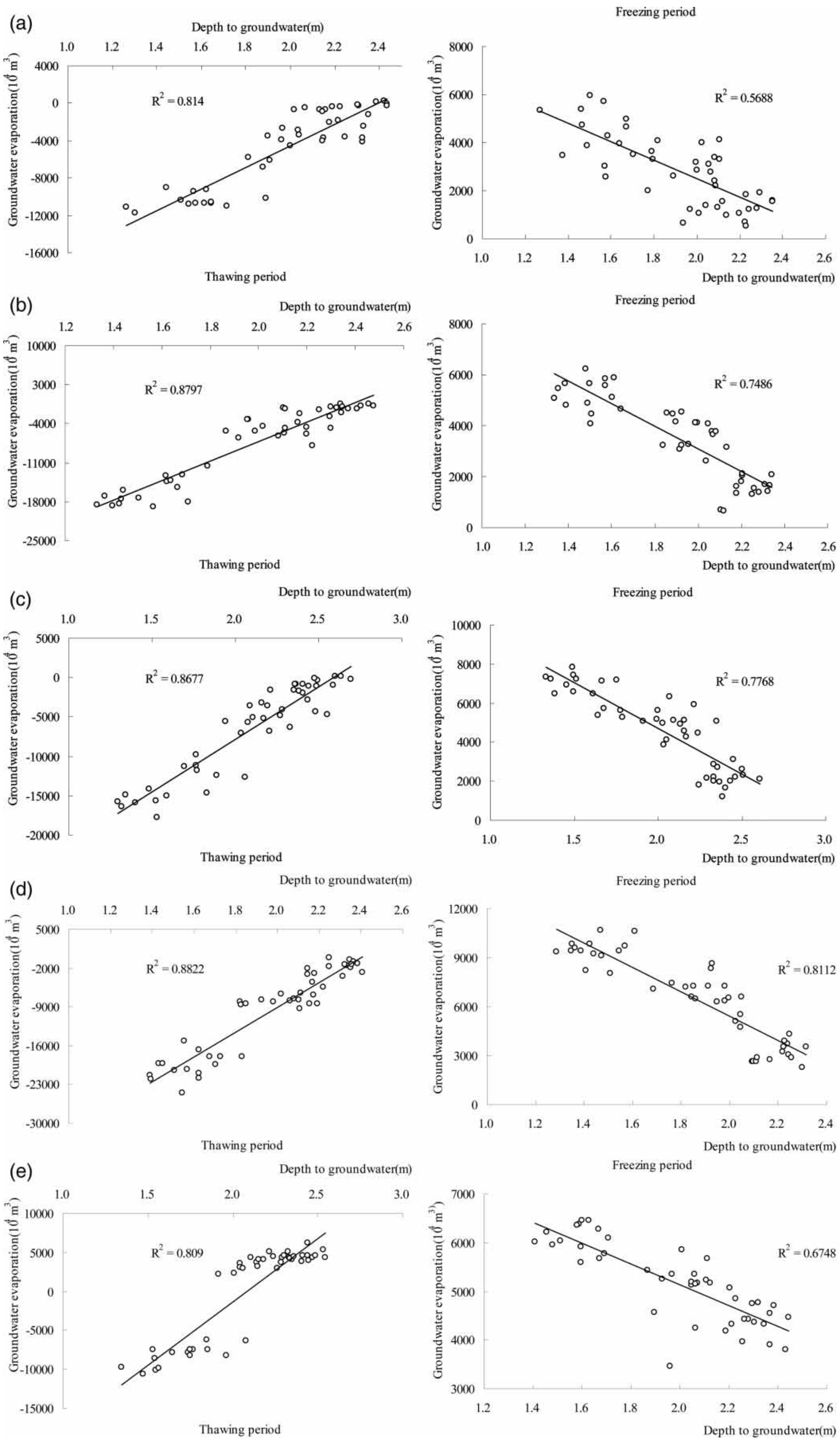

Figure 7 | Relationship between the evaporation and depth to groundwater in freezing and thawing periods. (a) Yigan, (b) Jiefangzha, (c) Yongji, (d) Yichang and (e) Wulate.

Table 2 | Hydrogeological parameters of the study area

Zone	μ	K	α	η	β	γ	θ
Yigan	0.038	8.54	0.15	0.47	0.37	0.28	0.20
Jiefangzha	0.054	5.14	0.10	0.51	0.34	0.27	0.20
Yongji	0.043	8.32	0.14	0.51	0.38	0.28	0.20
Yichang	0.038	7.36	0.12	0.43	0.40	0.28	0.20
Wulate	0.036	9.17	0.15	0.36	0.46	0.27	0.20

Validation of simulation model

The developed large-scale groundwater flow model is validated with the field observation data from 2000 to 2009. The discrepancy between measurement data and calculated results indicates the model can be applied to forecast the groundwater movement (Figure 8).

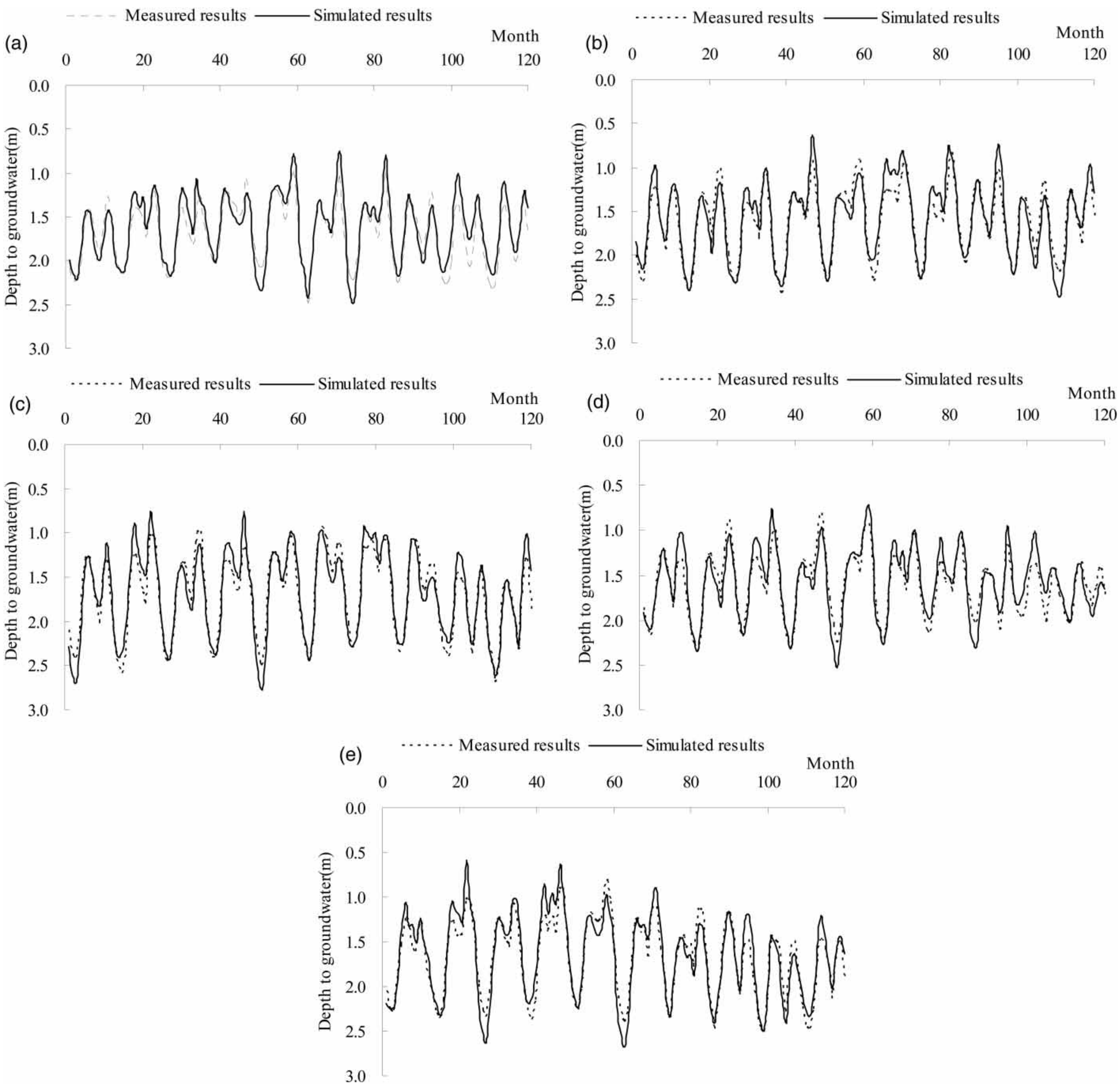

Figure 8 | Comparison of measured and simulated average depth to groundwater of each zone. (a) Yigan, (b) Jiefangzha, (c) Yongji, (d) Yichang and (e) Wulate.

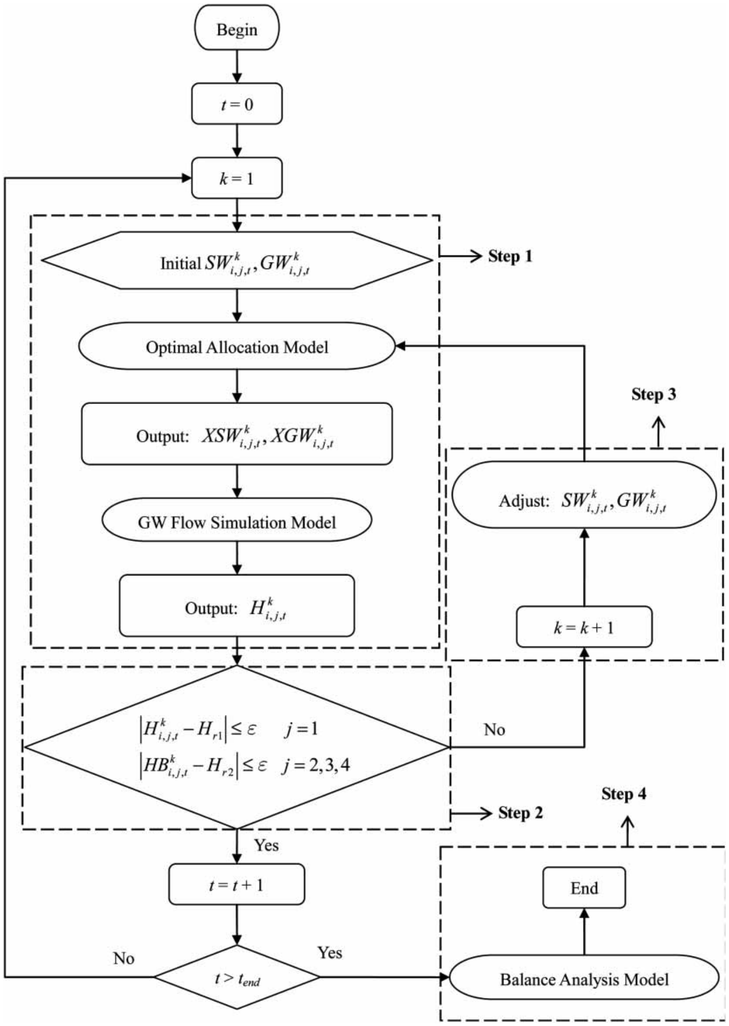

Figure 9 | Flow chart for sustainable utilization coupled management model. *Note*: The index *k* is the *k*th calculated value.

Conjunctive management model

In order to use water resources sustainably and control the groundwater level of each subdistrict reasonably, the sustainable utilization coupled management model is established by dynamically coupling a numerical simulation model with an optimum allocation model, based on transfer and feedback of common parameters, variables, and results between two models (Young & Bredehoeft 1972; Peng *et al*. 1992; Ma *et al*. 2004; Vedula *et al*. 2005). Figure 9 shows the flow chart for the sustainable utilization coupled management model.

In Figure 9, the initial value of $SW_{i,j,t}$ is given, and $GW_{i,j,t}$ can be evaluated according to Equation (14). Step 3 is the process of adjusting $SW_{i,j,t}$ and $GW_{i,j,t}$, and the methods used to adjust can be formulated as follows:

$$GW^k_{i,j,t} = XGW^{k-1}_{i,j,t} + (H^{k-1}_{i,j,t} - H_r) \cdot \mu_i \cdot F_{i,j}, j = 1 \tag{12}$$

$$GW^k_{i,j,t} = XGW^{k-1}_{i,j,t} + (HB^{k-1}_{i,j,t} - H_r) \cdot \mu_i \cdot F_{i,j}, j = 2, 3, 4 \tag{13}$$

$$SW^k_{i,j,t} = TWR_{i,j,t} - GW^k_{i,j,t} \tag{14}$$

where μ_i is specific yield of *i*th irrigation subdistrict, $F_{i,j}$ is the area of *j*th water use sector in *i*th irrigation subdistrict [L^2].

Finally, the computational program of the coupled model has been written with Fortran language, and validated with a series of multi-year observation data.

RESULTS AND DISCUSSION

Water allocation

Water resources for 2020 and 2030, including surface and groundwater, have been allocated optimally with the coupled model. The calculated results are given in Table 3.

Table 3 shows that the minimum water amounts for 2020 and 2030 do not exceed the national limited amount of 4.0×10^9 m^3/a. Of the total surface water supplies, irrigated water takes 85%, which is a decrease by 10% of that of the present year. On the other hand, the groundwater use efficiency has been strongly improved. As far as the whole irrigation district is concerned, the groundwater use efficiency is 82.5 and 83.0% in 2020 and 2030, respectively, but that of the present year is only 19%. The maximum value is 94% in Yichang irrigation subdistrict in 2020, and the minimum is 48% in Wulate irrigation subdistrict in 2020. In addition, monthly water allocation for the present year, 2020, and 2030 are calculated based on monthly water consumption and requirement. Figures 10 and 11 show the comparison of surface water and groundwater use in the present year, 2020, and 2030. From these two figures it can be seen that the groundwater use efficiency has been improved significantly during the irrigation period (from April to October). In contrast, the surface water has been reduced to less than 4.0×10^9 m^3/a. Therefore, the groundwater use efficiency can be improved by increasing the well–canal combined irrigation area and allocating the groundwater sensibly.

Groundwater level

According to the groundwater evaporation experiment results of Hetao Irrigation District, the groundwater evaporation is almost equal to zero when the groundwater depth is greater than 3 m. Consequently, in order to use the groundwater satisfactorily and maintain crop growth, the rational groundwater depths of irrigated and non-irrigated areas are around 2.5 and 3.0 m, respectively, according to other

Table 3 | The allocation results of water resources for 2020 and 2030 in Hetao Irrigation District (10^8 m^3)

				Agricultural water		Industrial water		Domestic water	Budget	
Year	Zone	Surface water supply	Groundwater supply	Surface water	Groundwater	Surface water	Groundwater	Groundwater	Surface water	Groundwater
2020	Yigan	3.164	0.885	2.733	0.504	0.431	0.038	0.122	0.000	0.221
	Jiefangzha	9.370	1.513	8.743	1.073	0.627	0.045	0.298	0.000	0.097
	Yongji	8.434	1.723	6.392	0.674	2.042	0.147	0.501	0.000	0.401
	Yichang	11.826	1.983	11.333	1.533	0.493	0.045	0.288	0.000	0.116
	Wulate	5.948	0.687	5.624	0.231	0.324	0.027	0.072	0.000	0.356
	Hetao Irrigation District	38.742	6.791	34.825	4.015	3.917	0.303	1.283	0.000	1.191
2030	Yigan	3.263	0.817	2.840	0.393	0.424	0.040	0.142	0.000	0.242
	Jiefangzha	9.398	1.525	8.780	0.919	0.618	0.046	0.334	0.000	0.227
	Yongji	8.203	1.797	6.182	0.883	2.020	0.143	0.596	0.000	0.176
	Yichang	11.714	1.705	11.226	1.141	0.488	0.044	0.326	0.000	0.193
	Wulate	5.663	0.672	5.342	0.300	0.321	0.026	0.080	0.000	0.266
	Hetao Irrigation District	38.241	6.517	34.371	3.636	3.871	0.298	1.478	0.000	1.105

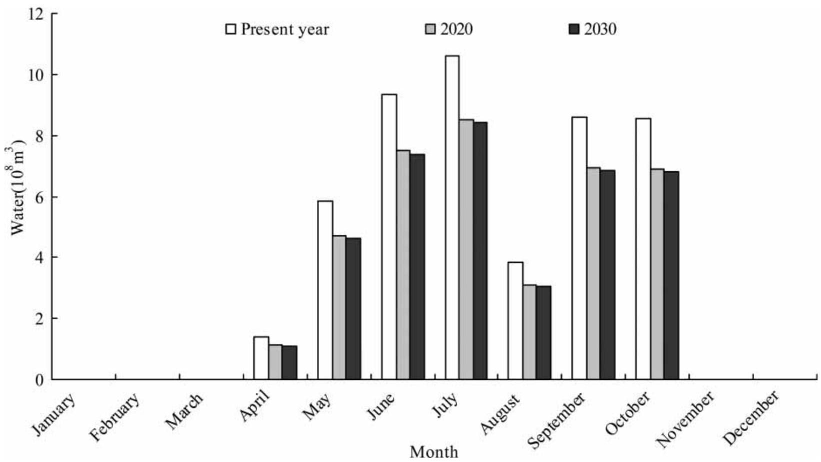

Figure 10 | Comparison of monthly surface water use between the present year, 2020, and 2030.

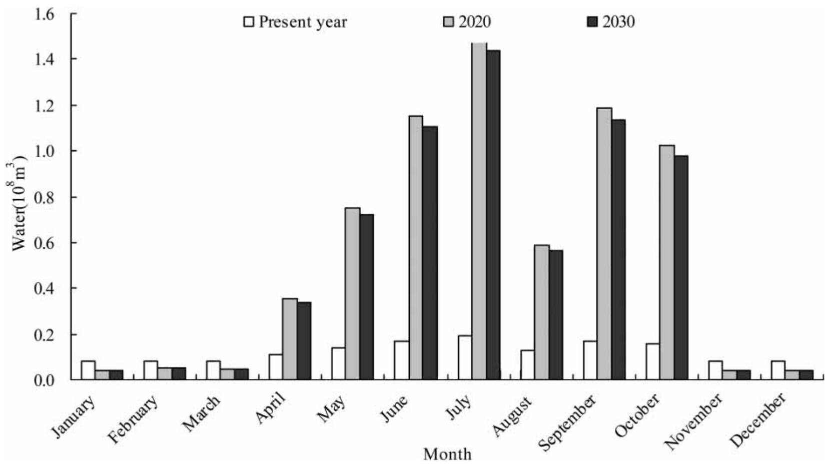

Figure 11 | Comparison of monthly groundwater use between the present year, 2020, and 2030.

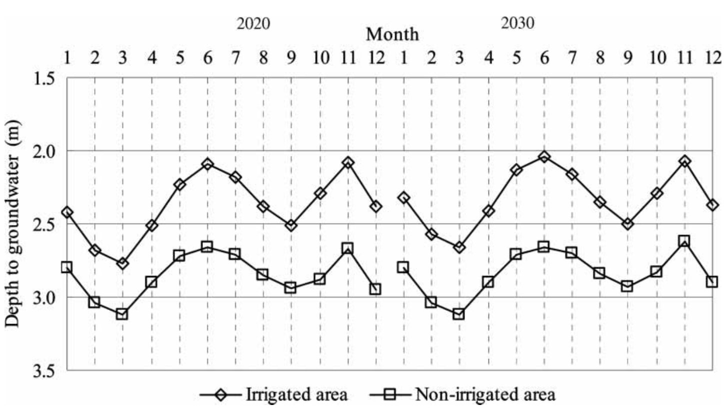

Figure 12 | Simulated results of the depth to groundwater for irrigated and non-irrigated areas.

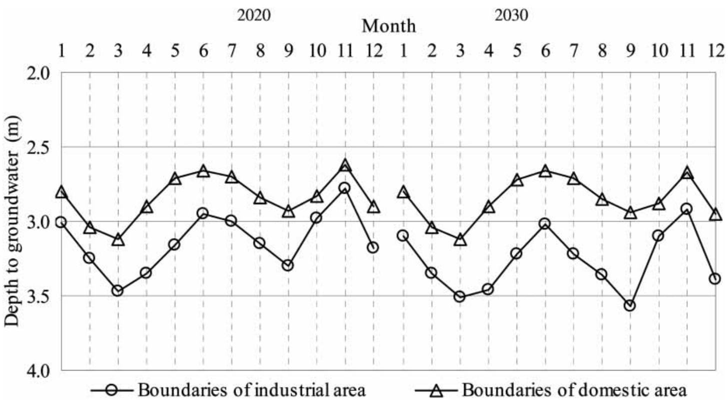

Figure 13 | Simulated results of the depth to groundwater for industrial and domestic areas.

experiment results and related data (Guo & Liu 2005; Yang *et al.* 2006). Besides, the groundwater depth of boundaries in centralized exploitation areas should also be controlled at around 3.0 m to avoid expansion of the depression cones. Based on the above-mentioned control principles, the groundwater depth of each area for 2020 and 2030 is simulated through running the coupled management model. The results are illustrated in Figures 12 and 13.

CONCLUSIONS

The sustainable utilization coupled management model is developed by dynamically coupling the conjunctive use optimal model based on linear programming with the groundwater simulation model. Applying this model to Hetao Irrigation District in China, an optimal conjunctive utilization scheme for surface and groundwater in 2020 and 2030 has been investigated. The results indicate that the water imported from the Yellow River can be reduced to the national limit amount of 4.0×10^9 m^3/a, by adjusting the well–canal irrigated area and industry structure appropriately, as well as conjunctive use of surface and groundwater.

Additionally, the groundwater table of each area can be controlled and the water use efficiency can be improved with the coupled management model. Therefore, the results shown in this paper are of practical significance for enhancing the efficiency of water use, improving the ecological environment, calculating water resources' carrying capacity scientifically, adjusting cropping patterns logically, intensifying the management of water resources and, lastly, allocating and using the limited water resources of the Yellow River basin effectively.

Finally, the conjunctive management model is a convincing model with some assumptions based on the long-term observed data. However, there exist some potential uncertainties in the model, such as parameters, constraints, and rainfall. How to quantify these with an appropriate method will be a focus for further study.

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