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PAPER

Ecology-oriented groundwater resource assessment in the Tuwei River watershed, Shaanxi Province, China

Z. Y. Yang[1,2,3] · **W.K. Wang**[1,2,3] · **Z. Wang**
G. H. Jiang[1,2,3] · **W. L. Li**[4]

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Abstract In arid and semi-arid regions, a close relationship exists between groundwater and supergene eco-environmental issues such as swampiness, soil salinization, desertification, vegetation degradation, reduction of stream base flow, and disappearance of lakes and wetlands. When the maximum allowable withdrawal of groundwater (AWG) is assessed, an ecology-oriented regional groundwater resource assessment (RGRA) method should be used. In this study, a hierarchical assessment index system of the supergene eco-environment was established based on field survey data and analysis of the supergene eco-environment factors influenced by groundwater in the Tuwei River watershed, Shaanxi Province, China. The assessment system comprised 11 indices, including geomorphological type, lithology and structure of the vadose zone, depth of the water table (DWT), total dissolved solids content of groundwater, etc. Weights for all indices were calculated using an analytical hierarchy process. Then, the current eco-environmental conditions were assessed using fuzzy comprehensive evaluation (FCE). Under the imposed constraints, and using both the assessment results on the current eco-environment situation and the ecological constraint of DWT (1.5–5.0 m), the maximum AWG (0.408×10^8 m^3/a or 24.29 % of the river base flow) was determined. This was achieved by combining the groundwater resource assessment with the supergene eco-environmental assessment based on FCE. If the maximum AWG is exceeded in a watershed, the eco-environment will gradually deteriorate and produce negative environmental effects. The ecology-oriented maximum AWG can be determined by the ecology-oriented RGRA method, and thus sustainable groundwater use in similar watersheds in other arid and semi-arid regions can be achieved.

Keywords China · Ecology · Arid regions · Groundwater/surface-water relations · Water table

Introduction

In arid and semi-arid regions, groundwater resources are very important for industry, agriculture, and human lives, and sometimes they are the only source of water available. At the same time, groundwater constrains the eco-environment because of its close relation with eco-environmental factors. Owing to the increasing exploitation of groundwater resources, the negative environmental effects induced by groundwater withdrawal are increasingly severe (Yang 2004; Yang et al. 2006; Yang and Wang 2009; Wang et al. 2011). In the European Groundwater Framework Directive, groundwater is viewed not only as a resource but also as a living ecosystem; moreover, groundwater assessment should include assessment of both the biological and ecological states. Groundwater fauna and bacterial communities could be used as biomonitoring indices of the ecosystem status (Griebler et al. 2010; Menció

✉ Z. Y. Yang
yangzeyu@chd.edu.cn

[1] School of Environmental Science and Engineering, Chang′an University, Xi′an 710054, Shaanxi, People's Republic of China

[2] Key Laboratory of Subsurface Hydrology and Ecological Effect in Arid Regions of Ministry of Education, Xi′an 710054, Shaanxi, People's Republic of China

[3] Engineering Research Center of Groundwater and Eco-Environment of Shaanxi Province, Xi'an 710054, Shaanxi, People's Republic of China

[4] Shaanxi Institute of Geo-environment Monitoring, Xi'an 710054, Shaanxi, People's Republic of China

and Mas-Pla 2010). Therefore, the assessment and determination of suitable groundwater yield are urgently needed for sustainable groundwater development. In Nebraska, USA, if a typical riverside well is pumped for 50 years and the effect of pumping on the river base flow is smaller than 10 %, then this exploitation scheme is deemed rational (Wang et al. 2011). In theory, sustainable groundwater yield can be summarized as the available yield that allows for normal long-term exploitation without any adverse effects under a rational development strategy while having the maximum social, financial, and environmental benefits (Yang et al. 2012; Shi et al. 2012). However, in practice, when the available yield is determined, the assessment model of the supergene eco-environmental effects induced by groundwater withdrawal (SEEIGW) is not coupled with regional groundwater resource assessment (RGRA) models. (Note, the term "supergene" relates to processes associated with or near to the ground surface.)

Numerical simulations are often used to predict the sustainable yield of groundwater (Kalf and Woolley 2005; Barthel et al. 2008); nevertheless, because of the complexity of human activities and the different practices around the world, such methods are not always effective. Consequently, other kinds of models and methods to assess groundwater resources have been proposed. First, evaluation models that integrated cost-benefit models, water-cycle simulation models, and optimization models were proposed. The integrated evaluation model of Shi et al. (2012) suggested that the optimized groundwater yield could be sustained by increasing the supply ratios of the reservoir (more intensive supply), which would also satisfy the ecological demand for water. Second, some models have been proposed that couple groundwater assessment models (GAM) and either (1) the process-based National Integrated Catchment-based Eco-hydrology (NICE) model, which simulates results that address the impact of groundwater-level change, sediment deposition, and nutrient availability on vegetation change, and improves the evaluation accuracy of nonlinear interactions and feedback of the hydrogeomorphology and vegetation dynamics in an ecosystem (Nakayama 2013), or (2) the eco-hydrological Soil and Water Integrated Model (SWIM) with good simulation results and satisfactory reproduction of the groundwater dynamics and eco-hydrological properties of forest stands at the regional scale in the federal state of Brandenburg of Germany (Hattermann et al. 2004; Wattenbach et al. 2005), or (3) a surface-water model with simulation results that suggest that large amounts of surface water move through an anoxic streambed, producing denitrification and nitrate loss, and show why nitrate is detected in nearly all stream samples but is never detected in any of the streambed or adjacent groundwater samples (Barlow and Coupe 2012). Third, some models were GAM under constraints such as water drawdown, ecological water demand, and critical depth of salinization with sustainable and effective use and good integrated benefits (Zhang et al. 2002).

Most of the research models and methods noted in the aforementioned have focused on certain aspects of the groundwater resource assessment or ecological assessment. The coupling between GAM and an eco-environmental assessment model (EAM) has not been reported. The relation between supergene ecological problems and RGRA was insufficiently considered in combined models. Furthermore, such models fall short of becoming an information platform and a method system of RGRA; however, Wang et al. (2011) proposed a method for the ecology-oriented RGRA. The Tuwei River watershed in Shaanxi Province, China, was used to assess the maximum AWG. The results of this case study are key references for determining the ecology-oriented allowable withdrawal and sustainable use of groundwater resources in similar watersheds of arid and semi-arid regions. The list of acronyms is provided in the Appendix.

Materials and methods

Watershed survey

The Tuwei River watershed (38°10′N to 39°10′N, and 109°45′E to 110°35′E) covers 3,294 km^2 and is located in the transitional zone between the Mu Us Sandy Land (Maowusu Desert) and the loess plateau in the eastern Ordos basin in Yulin City, Shaanxi Province, P.R. China (Fig. 1). It can be divided geomorphologically from the northwest to the southeast into an upland plain region with lakes (I), a desert region (II), a loess hills region overlying the sands (III), a region of loess ridges and hills (IV), and a valley region (V) (Fig. 2). The mean annual precipitation is 402 mm (1971–2011) and the mean annual evaporation is 1,853 mm (1971–2004; Meteorological Bureau of Shenmu County, Shaanxi Province, P.R. China). The Tuwei River, which has the lowest discharge base level in the watershed and whose mean annual runoff is 4.35 × 10^8 m^3, is the first-level branch of the Yellow River. The Quaternary strata comprise middle Pleistocene aeolian deposits (Q_2^{eol}), Epipleistocene aeolian deposits (Q_3^{eol}), and Epipleistocene alluvial and lacustrine deposits (Q_3^{al+l}), and Holocene aeolian deposits (Q_4^{eol}), lacustrine deposits (Q_4^{l}), and alluvial deposits (Q_4^{al}). The main aquifer is a porous phreatic water (Q_3^{al+l}).

Field survey

The field survey identified desertification, vegetation succession, and reduction of river base flow in this watershed. The controlling factors were geological, meteorological, hydrological, and human activities. Certainly human activities can affect groundwater quantity (including the water table) and

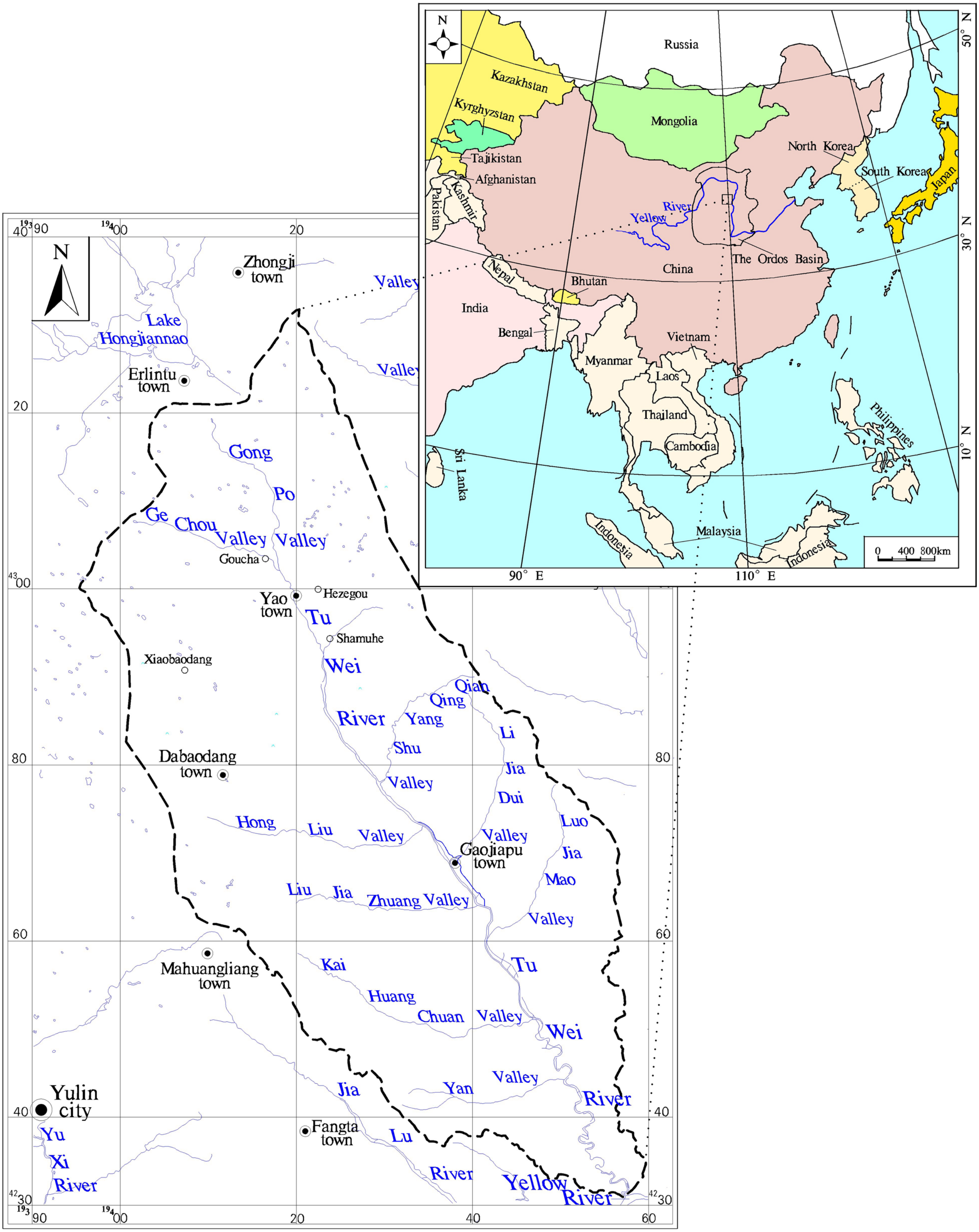

Fig. 1 Map of the Tuwei River watershed. The *dotted line* denotes the research area

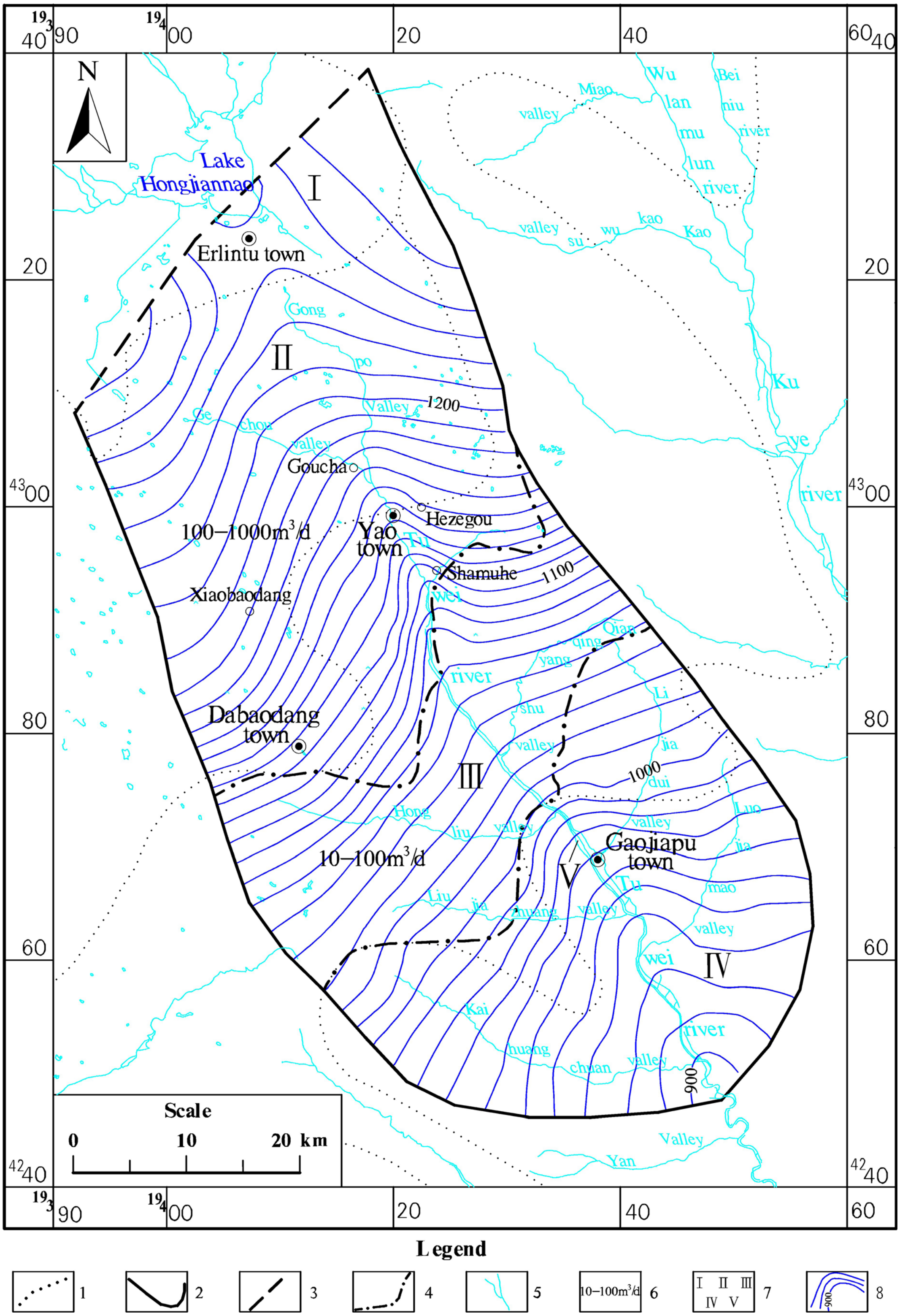

Fig. 2 Geomorphological types, hydrogeological concept model, and initial flow fields in the watershed. Legend: *1* border line of geomorphological types; *2* zero flow boundary; *3* known water level boundary; *4* border line of water yield property division; *5* rivers and their branches; *6* yield of a simple well; *7* geomorphological types—upland plain region with lakes (*I*), desert region (*II*), loess hills region overlying sands (*III*), loess ridges and hills region (*IV*), and valley region (*V*); *8* isopiestic contours (piezometric surface) and values for the phreatic water (m above sea level)

quality, involving either pumping or injection schemes (Yang 2004). Surface soils were sampled for analysis of particle-size distribution and soluble salts. The water content of surface soils was measured by oven-drying samples at 105–110 °C. Thirty vegetation quadrats of the typical plant population of herbs—*Salix mongolica*, *Artemisia sphaerocephala* Krasch, *Populus simonii* Garr, and *Salix matsudana*—were surveyed under different water-table conditions: DWTs of 0.0–1.0, 1.0–2.0, 2.0–3.0, 3.0–4.0, 4.0–5.0, and 5.0–6.0 m.

Groundwater level and vegetation growth indices

The groundwater levels of 30 wells were measured and the groundwater was sampled for chemical analysis. Then, the distribution maps of the total dissolved solids and chemistry of the phreatic aquifer were drawn. In addition, the dynamic water table (water level over time) data of 27 wells were collected. Based on these data, an initial phreatic water head flow field (Fig. 2) and distribution map of DWT were drawn for the watershed.

Vegetation growth indices include herb coverage, crown width and height, shoot length, coverage and ages of shrubs, and crown density, height, breast-height diameter and ages of trees. The crown height and width, shoot length of shrubs, and the breast-height diameters of trees were measured using steel tapes. The coverage of herbs and shrubs as well as the crown density of trees was measured by quadrat surveys of 10 m × 10 m grids. The ages of shrubs were acquired by interviewing the local residents and ages of the trees by counting the tree rings. All the data were used to classify the environmental state into excellent, good, average, poor, and very poor.

The ecology-oriented RGRA method

Based on the analysis of the assessment methods and cases of regional groundwater resources in China and other parts of the world, Wang et al. (2011) proposed a framework for an ecology-oriented RGRA method in arid and semi-arid regions (Fig. 3), combining the assessment practices of RGRA in the Junggar Basin, Tarim Basin, Gansu Corridor, and the blown-sand region of the northern Shaanxi Province in China.

The objective of the proposed method is to facilitate sustainable utilization of groundwater resources while respecting the eco-environment. The method seeks to uphold three principles: unite the assessment of surface water and groundwater; pay equal attention to groundwater quantity and quality; and encompass both groundwater resources and their relative eco-environment. There is a need to construct a hydrogeological conceptual model, a lumped parameter model, a distributed parameter model and an eco-environment assessment model based on groundwater change; thus, the method introduces three constraint conditions of groundwater quantity, water-table depth, and groundwater quality, and develops an information system platform for eco-environment assessment.

In the Tuwei River watershed, the key environmental aspects include swampiness, soil salinization, desertification, and vegetation degradation induced by groundwater withdrawal. So the assessment objective is to determine maximum allowable withdrawal for both sustainable utilization of groundwater resources and ecological sustainability. The method mainly comprises the following four steps.

Development of the assessment platform

Based on the spatial databases of the ecological environment, an ecological environment assessment information system (EEAIS) was developed using visual C++ 6.0 as the development language and MAPGIS 6.7—a Chinese geographical information system (GIS) software (Zondy Cyber 2014)—as the development platform. EEAIS consists of eight menus: system management, project management, graphics management, attribute management, spatial analysis, basic tools, system settings, and help. The spatial analysis menu is divided into basic and special. The special analysis, the most pivotal part of the system, includes a synthetic index model, a fuzzy comprehensive evaluation (FCE) model, a fuzzy iterative self-organizing data analysis technique model, and the neural network of a back-propagation model. This system is the information platform and assessment tool for visualizing and integrating the assessment of the ecological environment with an early warning system.

The establishment of the assessment index system and standards

The assessment indices of the factors in SEEIGW were determined by analyzing field survey data. The factors were then arranged to establish the hierarchical assessment index system of SEEIGW (Yang 2004). The factors of the SEEIGW objective layer (Fig. 4 and Table 1) are the geological characteristics (R_1), hydrogeology (R_2), and meteorology and hydrology (R_3). The factors of the criterion layer are the geomorphic type (I_1), the lithology and structure of the vadose zones (I_2 and I_3), the depth of the water table (DWT) (I_4), the total dissolved solids content (I_5), the groundwater chemistry (I_6), the mass of water relative to the mass of dry soil particles in the vadose zones (I_7) (Hillel 2004), the percentage of salt weight in 100 g of soil in the vadose zones (I_8), the precipitation (I_9), the impact of the water table on evaporation (I_{10}), and the ratio of the decrease of river base flow to the total river base flow (I_{11}).

Values for I_1 were determined based on the relation between geomorphological types and the supergene eco-environment. The values for I_2 and I_3 were determined by the lithology and structure of the vadose zones. The values for I_4 were based on the distribution map of DWT and Table 2, and those of I_5 and I_6 were interpolated from the groundwater samples. The values for I_7 and I_8 were interpolated by

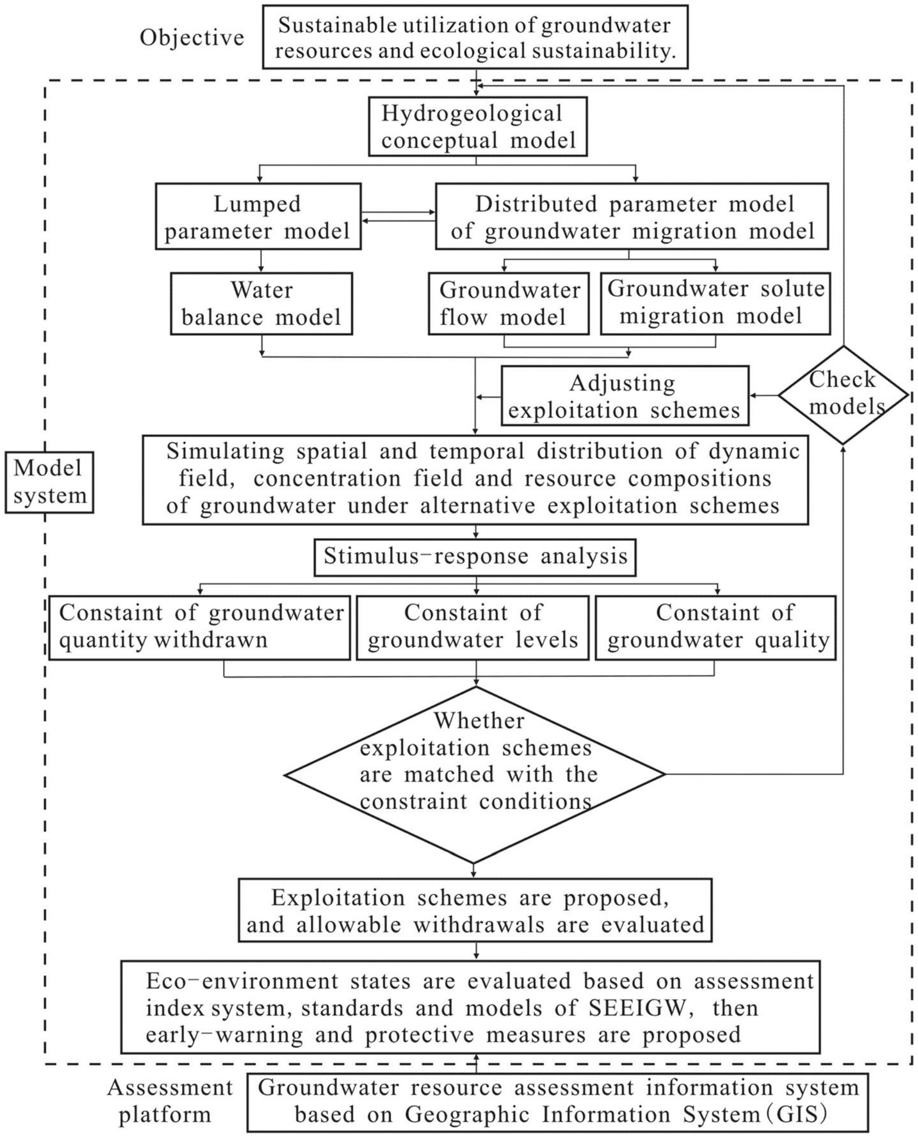

Fig. 3 Concept framework of the ecology-oriented regional groundwater resource assessment (RGRA) method in arid and semi-arid regions (modified according to Wang et al. 2011)

analyzing the results of the surface soil samples, and those for I_9 were acquired from the contour map of the average annual precipitation. For I_{10}, the values were determined from the effect of the water table on evaporation, and for I_{11}, they were determined by the percentage of the decreased river base flow relative to the total river base flow in the valleys.

Standard values for I_1–I_4, I_6, I_7, and I_9 were determined according to their influence on the eco-environment by field surveys of the watershed. The I_5 values were <1, 1–3, 3–10, 10–50, and >50 g/L, corresponding to freshwater, brackish water, salt water, saline water, and brine, respectively. The I_8 values were determined according to the watershed state with reference to its standard value in the Xinjiang Uygur Autonomous Region of P. R. China (Luo et al. 1985). The I_{10} values were determined according to the DWT and the critical evaporation depth of groundwater in the watershed. The I_{11} values were determined according to previous research (Fan 1996; Alley et al. 1999; Sophocleous 2000; Alley and Leake 2004; Maimone 2004; Wang et al. 2011) and watershed states (Table 1).

Models

Four models were considered.

The lumped parameter model The lumped parameter model (Scanlon et al. 2002) is a water balance model. In the watershed, the natural groundwater resource yields are 3.86×10^8 m^3/a and 3.59×10^8 m^3/a, calculated using the total recharge method and the total discharge method, respectively. The river base flow was determined to be 1.68×10^8 m^3/a by using the base flow index (BFI; Qian et al. 2004). Conservatively, the natural groundwater resource (the upper limit of AWG) was estimated to be

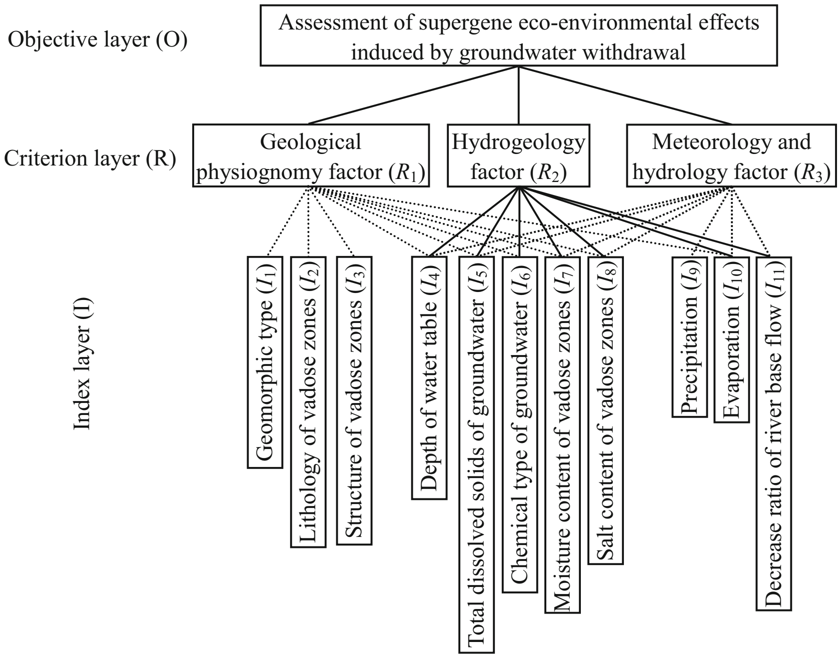

Fig. 4 The hierarchical assessment index system of SEEIGW

3.59×10^8 m^3/a. The river base flow accounted for 46.8 % of the natural groundwater resource

The hydrogeological conceptual model The hydrogeological conceptual model is shown in Fig. 2. The main aquifer was the porous phreatic aquifer (Q_3^{al+l}), which is characterized by medium-to-fine sand and silt-to-fine sand. Based on the geological conditions and the groundwater head flow field: the northwestern boundary of the conceptual model is Hongjiannao Lake; the western boundary is the water divide

Table 1 Index standard values of the supergene eco-environmental effects induced by groundwater withdrawal

Level Indices		Excellent eco-environment	Good eco-environment	Average eco-environment	Poor eco-environment	Very poor eco-environment
R_1	I_1	Valley region	Loess ridges and hills region	Upland plain region with lakes	Loess hills region overlying sands	Desert region
	I_2	Silty mild clay, sand loam	-	Silty sand loam, mild clay	Silt and fine sand, sand loam	Sand loam, cobblestones
	I_3	Q_3^{eol} +Q_2^{eol} loess	-	Q_2^{eol} loess	-	Q_3^{al+l} alluvial and lacustrine deposits
R_2	I_4 (m)	1–3	<1	3–5	5–8	>8
	I_5 (g/L)	<1	1–3	3–10	10–50	>50
	I_6	HCO_3–Ca	HCO_3–Ca·Mg (Mg·Ca)	HCO_3–Ca·Na·Mg	$HCO_3 \cdot SO_4$ ($SO_4 \cdot HCO_3$)–Ca·Mg	-
	I_7 (%)	>6	4.667–6	3.333–4.667	2–3.333	<2
	I_8 (%)	<0.2	0.2–1.0	1.0–2.0	2.0–3.0	>3.0
R_3	I_9(mm)	>440	-	410–440	-	<410
	I_{10} (I_4)	Weak influence (>3.0 m)	-	A little influence (2.5–3.0 m)	-	Intense influence (<2.5 m)
	I_{11} (%)	<10	10–20	20–30	30–40	>40

R_1 denotes the geological physiognomy factor; R_2 denotes the hydrogeology factor; R_3 denotes the meteorology and hydrology factor.

I_1 denotes the geomorphological type index; I_2 and I_3 correspond to the lithology and structure indices of the vadose zones; I_4 denotes the depth index of the water table; I_5 denotes the total dissolved solids index; I_6 denotes the chemical type index of groundwater; I_7 denotes the mass index of water relative to the mass of dry soil particles in the vadose zones (Hillel 2004); I_8 denotes the percentage index of salt weight in 100 g of soil in the vadose zones; I_9 denotes the precipitation index; I_{10} denotes the impact index of the water table on evaporation; I_{11} denotes the percentage index of the decreased river base flow relative to the total base flow

Table 2 Main characteristics of the ecologically important depth of the water table (*DWT*) in the Tuwei River watershed

Subsurface condition	DWT (m)	Main characteristics
Saline DWT	0–1.5	• Herbage production is large; moreover, trees and shrubs grow because of the high moisture content in the aeration zones •Soil salinization owing to the accumulation of salt at the ground surface • Phreatic water evaporates strongly; therefore, the ineffective evaporation is large • The base flow of rivers keeps steady. There are also large and small lakes and wetlands • The eco-environment of rivers is excellent
Best DWT	1.5–3	• Trees and shrubs grow properly because of the appropriate moisture content that satisfies the physiological needs of the roots in the aeration zone. Herbage production declines but herbage can grow • The ineffective evaporation of phreatic water declines • The base flow of rivers decreases slightly
Tolerable DWT for trees and shrubs	3–5	• Trees and shrubs can grow normally because of the moisture content that satisfies the basic physiological needs of the roots in the aeration zone. Trees can imbibe groundwater from the main root system by extending downward. Shrubs can imbibe soil water from sectors of relatively high moisture in the subsurface aeration zone. Herbage does not emerge • Phreatic water stops evaporating • Base flow of rivers decreases and parts of wetlands are dry
DWT warning signs	5–8	• Trees and shrubs grow unhealthily because of the physiological aridity. Shrubs imbibe soil water from sectors of relatively high moisture in the relatively deep aeration zone. Root system of trees imbibe groundwater but part of branches wither • The base flow of rivers decreases sharply and parts of their tributaries are drying up. The majority of wetlands are dry
DWT for decline of trees	8–15	• Vegetation degrades and soil desertification exists because the moisture content declines sharply. Shrubs imbibe soil water from sectors of relatively low moisture content in the deep aeration zone. Trees imbibe groundwater with difficulty and degrade. Some become short trees, baldheaded, and the majority of their branches wither • The base flow of rivers decreases more sharply and some dry up • The eco-environment tends to deteriorate
DWT for trees to wither	>15	• Vegetation degrades and even dies, and soils undergo desertification. Trees only imbibe subsurface moisture content by the horizontal root system, and the majority of their branches wither or die. Shrubs degrade because the majority of moisture is pellicular, with short crown height and crown length • Main rivers are drying up • Vegetation coverage declines obviously, which promotes desertification and leads to the activation of formerly stabilized dunes and semi-stabilized dunes

between the Tuwei River watershed, the Yuxi River watershed and the Jialu River watershed; the eastern boundary is the water divide between the Tuwei River watershed and the Kuye River watershed; and the southern boundary is the water divide between the Kaihuangchuan Valley and the Yan Valley. Except for the northwestern boundary, which is the known water level boundary, all of the others were zero flow boundaries. The upper boundary is the phreatic water table and the lower boundary is the Jurassic bed rocks, which act as an aquifuge. Hence, the groundwater flow is heterogeneous, isotropic, two-dimensional, and non-steady phreatic flow.

The distributed parameter models The distributed parameter models include a flow model and a solute transport model of groundwater. In this region, the groundwater quality is good; thus, the solute transport model was not considered. According to the aforementioned conceptual model, under the initial head flow field and current exploitation, the mathematical model for groundwater flow is given in Eq. (1) .

$$\begin{cases} \frac{\partial}{\partial x}\left[K(h-B)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K(h-B)\frac{\partial h}{\partial y}\right]+W-\sum_{i=1}^{n}Q_i\delta(x-x_i,y-y_i) \\ =\mu\frac{\partial h}{\partial t}, \quad x,y\in\Omega, \quad t>0 \\ h(x,y,0)=h_0(x,y), \quad x,y\in\Omega \\ h(x,y,t)|_{\Gamma_1}=f(x,y,t), \quad x,y\in\Gamma_1, \quad t>t_0 \\ \frac{\partial h}{\partial n}|_{\Gamma_2}=0, \quad \Gamma_2\in\Omega \end{cases} \tag{1}$$

where:

W is the recharge intensity (m^3/m^2/day), $W = W_1 - W_2$
W_1 is the recharge intensity of precipitation (m^3/m^2/day)
W_2 is evaporation intensity (m^3/m^2/day)

Q_i is the pump discharge of the pumping wells in the source field (water head areas) within the boundary of the research area [Ω (m^3/day)] with coordinates (x_i, y_i)
$\delta(x-x_i, y-y_i)$ is the δ well function on (x_i, y_i) (1/m^2)
h_0 is the initial water level function
h is the water head at any time
$f(x, y, t)$ is the known water head function
K is the hydraulic conductivity (m/day)
μ is the specific yield
B is the elevation of the aquifer basement
Ω is the boundary of the research area, which is constituted by Γ_1 and Γ_2
Γ_1 is the known water head boundary of the research area
Γ_2 is the zero flow boundary of the research area
n represents outward normal direction of boundaries

The mathematical model was solved by using the finite-element method. The computational domain, with an area of 3,270.51 km^2, was subdivided into 484 triangle meshes. The source and sink terms include precipitation and evaporation. The precipitation intensity was determined according to the monthly precipitation at the weather station in Shenmu County, Shaanxi Province. The evaporation intensity of the phreatic water was determined according to the different DWT values: less than 1 m, 1–3 m, and greater than 3 m. If the DWT was greater than 3 m, no evaporation occurred. The hydraulic conductivity, specific yield, and coefficient of precipitation recharge were taken from the literature. The time step was 1 day. The model was calibrated by minimizing the error between observations and calculations for the 27 dynamic wells, and between the calculated river discharge from the model and the river base flow using the base flow index. Finally, the hydraulic conductivity and specific yield of the different geomorphological types were determined.

In general, there are two kinds of groundwater exploitation methods. One involves a well field for concentrated water supply (WFCWS), which means exploitation according to the proposed groundwater source fields in the past, whereas the other method is associated with a well field for deconcentrated water supply (WFDWS), which means regional exploitation by means of uniform well configuration.

- *WFCWS*. In this watershed, five groundwater source fields were developed in the sandy and loess hill region overlying the sands, and their total allowable withdrawal assessed in the past is 1.133 × 10^8 m^3/a. Goucha (AWG 0.548 × 10^8 m^3/a), Hezegou (AWG 0.057 × 10^8 m^3/a), Shamuhegou (AWG 0.078 × 10^8 m^3 /a), Xiaobaodang (AWG 0.223 × 10^8 m^3/a), and Dabaodang (AWG 0.228 × 10^8 m^3/a) had exploitation intensities of 7.37 × 10^{-3} m^3/m^2/day, 4.31 × 10^{-3} m^3/m^2/day, 5.54 × 10^{-3} m^3/m^2/day, 9.37 × 10^{-3} m^3/m^2/day, and 7.08 × 10^{-3} m^3/m^2/day, respectively. In the Goucha source field, 0.128 × 10^8 m^3/a was the reserved river base flow. Based on the uniform well configuration, with 600-m spacing between each well, the groundwater withdrawal was simulated (Fig. 2).
- *WFDWS*. Beginning with the same groundwater withdrawal as WFCWS and then progressively decreasing by 2–4 %, 25 exploitation schemes were designed. The exploitation withdrawal was assigned by using the ratios of the mean yield of a simple well in each water-yield property division relative to the sum of the mean yield of a simple well in the middle water-yield property division and the poor water-yield property division. Because the groundwater in the loess ridge and hill region was extremely poor in quantity, the groundwater exploitation was limited to the other regions. Then the groundwater withdrawals of the 25 exploitation schemes were simulated (Table 3).

The eco-environmental assessment model There are many eco-environmental assessment methods such as the analogy analysis method, the list method, the ecological map method, the synthetic index method, and the analytical hierarchy process (AHP) method (Zuo et al. 2001). FCE shows fuzzy boundaries and determines the assessment levels according to the maximum membership by the compositional operation between weight sets and monothetic factor sets. The mathematic expression of this model is

$$B = W \circ R \tag{2}$$

where B represents the membership values, W represents the weight values of each index, R denotes the monothetic factor values of each index, and $\circ$ represents the compositional operation between the weight sets and monothetic factor sets.

In this watershed, the weight vector (I_1, I_2, I_3, I_4, I_5, I_6, I_7, I_8, I_9, I_{10}, I_{11}), (0.068, 0.048, 0.048, 0.260, 0.119, 0.050, 0.178, 0.079, 0.050, 0.055, 0.043) was determined by the AHP method (Yang 2004).

To assess the current situation in the study area, 500 assessment units were subdivided to form an assessment unit layer using a 2.5-km square mesh. By union analyses between the assessment unit layer and 11 assessment index layers in the EEAIS, the last assessment index layer was acquired by integrant editing and correction. If a unit was intersected in more than one part, the value of the unit was determined by that of the part for which the area was maximum. The score of each index in each unit was assigned 0.1 to 10, corresponding to excellent and very poor eco-environmental levels, respectively. The other eco-environmental levels between excellent and very poor were interpolated between 0.1 and 10.

Table 3 Exploitation schemes by well fields for deconcentrated water supply (WFDWS)

Exploitation scheme	Total withdrawal (10^8 m^3/a)
No. 1	1.133
No. 2	1.088
No. 3	1.043
No. 4	0.997
No. 5	0.952
No. 6	0.907
No. 7	0.861
No. 8	0.816
No. 9	0.771
No. 10	0.725
No. 11	0.680
No. 12	0.657
No. 13	0.635
No. 14	0.612
No. 15	0.589
No. 16	0.567
No. 17	0.544
No. 18	0.521
No. 19	0.499
No. 20	0.476
No. 21	0.453
No. 22	0.431
No. 23	0.408
No. 24	0.385
No. 25	0.363

Eco-environmental assessment was undertaken for the different abstract schemes. Except for the DWT and ratio of the decrease of the river base flow, the indices changed little based on the annual averages; hence, the changes in the other indices were neglected. In accordance with the flow chart (Fig. 5), the assessment data were updated by DWT and the decrease in the river base flow predicted by the numerical simulation model. Then the eco-environmental assessment examined different exploitation scenarios.

Constraints

The constraints include the quantity and quality of groundwater. The first constraint is the ecological impact associated with DWT. The relation between DWT and its relative eco-environment was determined by researching the relation between DWT and vegetation growth, the base flow of the rivers and lakes, and the land desertification (Table 2). The DWT associated with ecological safety was 1.5–5.0 m, which was the basic evidence needed to regulate and control the water table, to determine the exploitation mode, and to assess AWG; therefore, the ecological constraint condition of the watershed was a DWT of 1.5–5.0 m in the numerical simulation.

The second constraint is the groundwater quantity withdrawn. The AWG should be smaller than 3.59×10^8 m^3/a, the natural groundwater resource in the watershed. The third constraint is the groundwater quality. The groundwater chemistry is characterized by HCO_3–Ca type and the total dissolved solids content is less than 1.0 g/L; hence, the groundwater quality is good and this constraint condition is ignored.

Results and discussion

Current situation assessment

The current condition assessment results were acquired on the basis of EEAIS (Fig. 6). The assessment results show that the environmental conditions were excellent or good in the upland plains with lakes (I) and in the region of loess ridges and hills (IV), average in the valley region (V), poor in the desert region (II), and very poor in the region of loess hills overlying sands (III). The key regions for protection were the desert region and the loess hill region overlying the sands. Because DWT in the southern part of the watershed is deeper than 8 m, SEEIGW is not significant in the loess ridge and hill region; therefore, the eco-environmental assessment domain is slightly smaller than the watershed. For very small abstractions of groundwater resources, the assessment results can be regarded as the eco-environmental background and can be used to judge whether one area is under stress.

Ecology-oriented RGRA of different exploitation scenarios

The ecology-oriented RGRA method (as presented in the previous section) was used in different exploitation scenarios (Fig. 3).

Scenario 1 *WFCWS (concentrated water supply).* According to the first exploitation scenario (Table 3), i.e., after exploitation for 10 years, the pattern of the groundwater flow field remarkably changed, the water table declined persistently and severely, the mean water head drawdown of the wells was bigger than 10 m, and even the maximum water head drawdown was up to 38.79 m in the Xiaobaodang source field. The upstream branches of the river became discontinuous and its base flow decreased by 19.42×10^4 m^3/day; i.e., 42.2 % of the

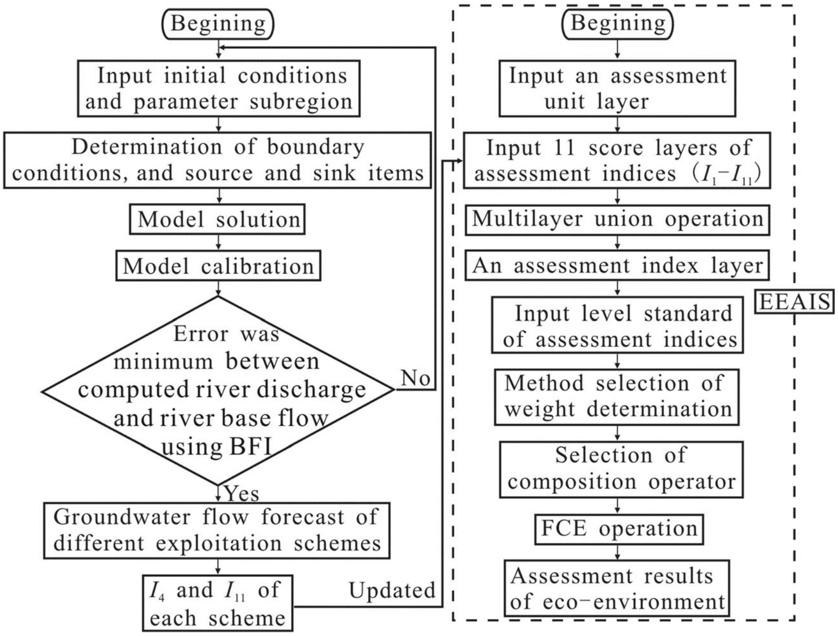

Fig. 5 The assessment flow chart of the ecology-oriented RGRA based on the ecological environment assessment information system (EEAIS). *BFI* base flow index, *FCE* fuzzy comprehensive evaluation

total base flow; therefore, this exploitation scenario was not sustainable.

Scenario 2 *WFDWS (deconcentrated water supply).* Comparing the numerical simulation results of the 25 schemes, and assigning exploitation for 10 years, the calculation results for scheme No. 1 were significantly different. However, those for schemes No. 23 and No. 24 were only slightly different. For schemes No. 23 and No. 24, after exploitation for 10 years, the distribution of DWT was closest to that of the current conditions, and the eco-environmental assessment results were similar and also to the current conditions based on EEAIS. Scheme No. 23, with exploitation of 0.408×10^8 m^3/a, accounted for 11.4 % of the total groundwater withdrawal, and the river base flow decreased by 8.82 %; thus, it could ensure both the minimum effect of groundwater exploitation on the ecological environment and the maximum withdrawal (Fig. 7). Thus, the exploitation of 0.408×10^8 m^3/a was the maximum allowable and the withdrawal was the most sustainable. Moreover, the assessment results also suggest that the traditional total groundwater withdrawal of 1.133×10^8 m^3/a is obviously too great; hence, the total groundwater withdrawal of the watershed should be assessed under the same flow field at the watershed scale.

In this study, the coupling of groundwater models and an eco-environmental assessment model was implemented under the constraint conditions of the current eco-environment, and the relation between the supergene ecological problems and RGRA was considered. In fact, the EEAIS provided a highly efficient and visualized assessment platform based on GIS, and the eco-environmental assessment results based on the assessment index system of SEEIGW can effectively check and interactively modify the different groundwater exploration schemes. Compared with the visualized assessment results of the current eco-environmental conditions, more and better exploitation schemes can be proposed, which can aid the decision-making based on different preferences. Therefore, it is possible to select the most appropriate exploitation scheme and determine the maximum AWG.

Previous studies have shown that 10 % of the total recharge is a conservative yield, the maximum yield is 25 % in arid regions, 40 % is the upper limit in semi-arid regions, and more than 70 % is unsustainable (Fan 1996; Alley et al. 1999; Alley and Leake 2004; Sophocleous 2000; Maimone 2004; Wang et al. 2011). Besides, referring to river base flow, if the effect of riverside exploitation on the river base flow is smaller than 10 %, then this exploitation scheme is considered rational (Wang et al. 2011). In the Tuwei River watershed, the maximum AWG accounted for 11.4 % of the total natural groundwater resources; moreover, its effect on the river base flow is a decrease by 8.82 %. As a result, it is a reasonable and a conservative yield; however, the eco-environmental assessment results of the EEAIS shows that it is the maximum yield. In this sense, the groundwater yield demonstrated previously was too high. Of course, for this kind of watershed, in which the river base flow accounts for about 50 % of the total recharge, the demonstrated method (which relates to 10 % of the total recharge) may not be the best. Perhaps, AWG should be demonstrated by another method and 25 % of the river base flow is possibly better. Nevertheless, more cases should be studied and more and longer exploitation

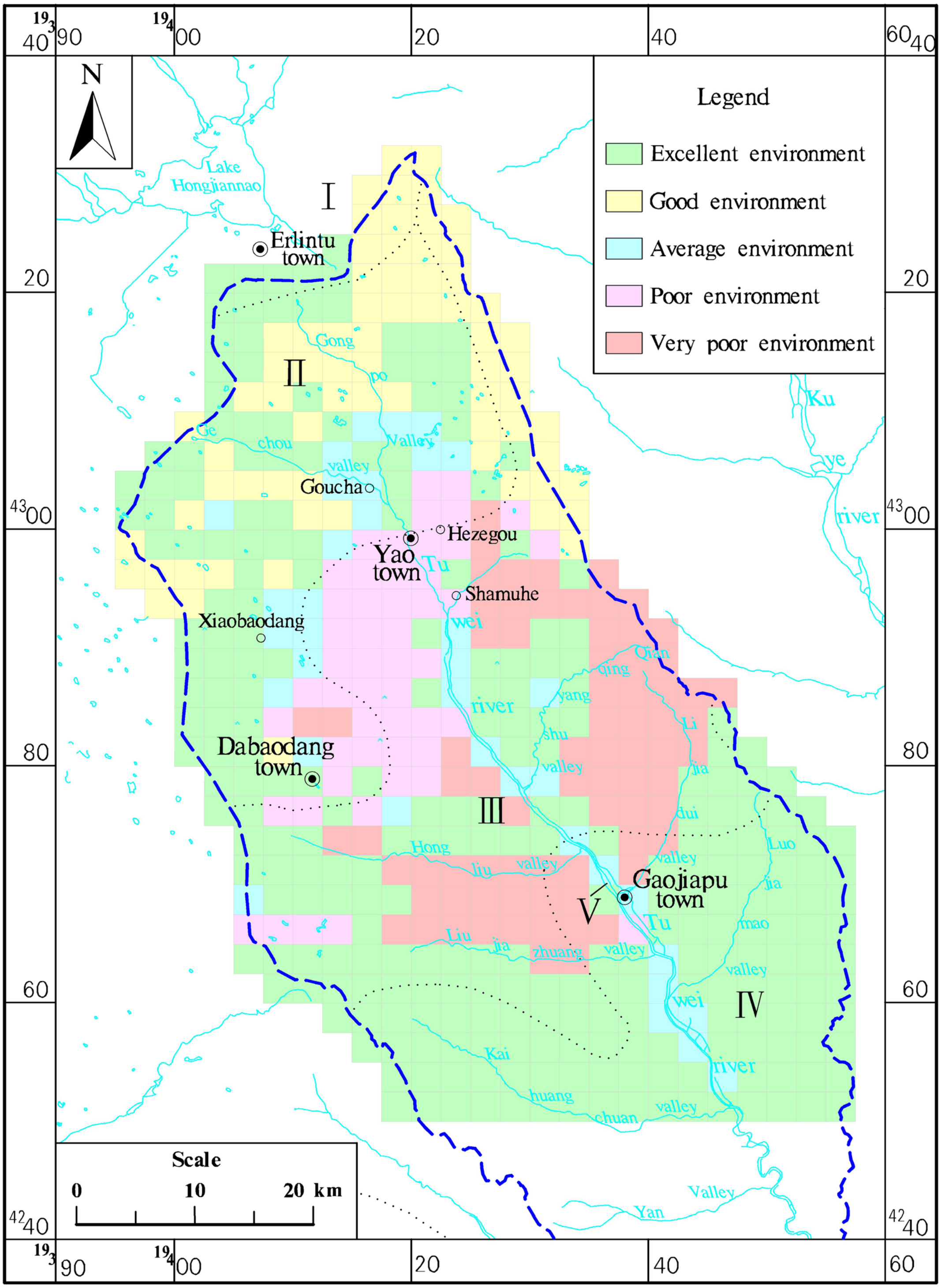

Fig. 6 The current situation assessment results on the ecological effect induced by groundwater withdrawal using the fuzzy comprehensive evaluation (FCE) in the watershed

practices should be validated. For extremely vulnerable watersheds, it is strongly recommended to couple GAM and EAM using the constraints of current eco-environmental conditions, ecologically constraining DWT, and groundwater quality.

In this study, the coupling between GAM and EAM is not restrictive. In the future, an integration between the GAM and EAM should be further developed with respect to the EEAIS. In addition, the conceptual framework of the ecology-oriented RGRA method should couple an ecohydrological soil and water integrated model or NICE model, and SEEIGW should include biological indices in groundwater such as biota and bacterial communities (Griebler et al. 2010; Menció and Mas-Pla 2010).

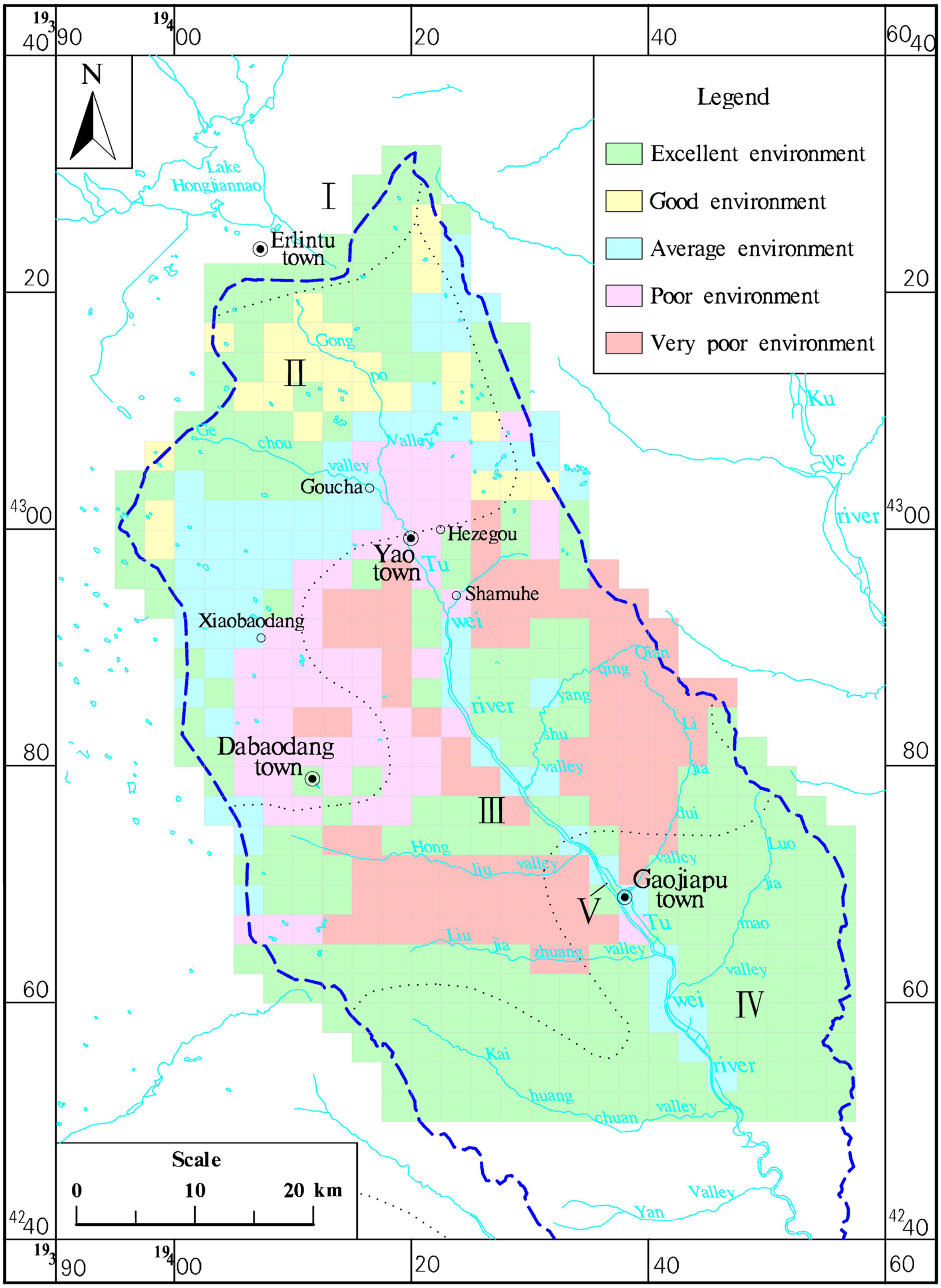

Fig. 7 The assessment result for the No. 23 scheme, with exploitation of 0.408×10^8 m^3/a, on the ecological effect induced by groundwater withdrawal using the fuzzy comprehensive evaluation (FCE) in the watershed

Conclusions

In the Tuwei River watershed, the natural groundwater resources (3.59×10^8 m^3/a) were assessed by a water balance model. The river base flow was 1.68×10^8 m^3/a. Using the 26 exploitation schemes in WFCWS and WFDWS, the allowable withdrawals of groundwater were simulated by using a heterogeneous, isotropic, two-dimensional, non-steady phreatic flow model. On the EEAIS platform, based on the assessment index system of SEEIGW, the current conditions were assessed by FCE. Using updated DWT data and the decrease of the river base flow forecast by the numerical simulation model, the environmental conditions of all 25 schemes were assessed by FCE. Under the ecological constraint of 1.5–5.0 m DWT, the maximum AWG was $0.408 \times 10^8\ m^3/a$, which is 11.4 % of the total recharge and 25 % of the river base flow based on the ecology-oriented RGRA method.

This method is a feasible method to assess AWG of similar watersheds. The results provide evidence for determining the maximum AWG and reasonable exploitation schemes of groundwater resources, and aid the coordinated development of supergene eco-environments in watersheds of arid and semi-arid regions.

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Appendix

AHP	Analytical hierarchy process
AWG	Allowable withdrawal of groundwater
BFI	Base flow index
DWT	Depth of the water table
EAM	Eco-environmental assessment model
EEAIS	Ecological environment assessment information system
FCE	Fuzzy comprehensive evaluation
GAM	Groundwater assessment models
NICE	Process-based national integrated catchment-based ecohydrology
RGRA	Regional groundwater resource assessment
SEEIGW	Supergene eco-environmental effects induced by groundwater withdrawal
WFCWS	Well field for concentrated water supply
WFDWS	Well field for deconcentrated water supply

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