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An ecology-oriented exploitation mode of groundwater resources in the northern Tianshan Mountains, China

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ABSTRACT

In recent years, ecological degradation caused by irrational groundwater exploitation has been of growing concern in arid and semiarid regions. To address the groundwater-ecological issues, this paper proposes a groundwater-resource exploitation mode to evaluate the tradeoff between groundwater development and ecological environment in the northern Tianshan Mountains, northwest China's Xinjiang Uygur Autonomous Region. Field surveys and remote sensing studies were conducted to analyze the relation between the distribution of hydrological conditions and the occurrence of ecological types. The results show that there is a good correlation between groundwater depth and the supergene ecological type. Numerical simulations and ecological assessment models were applied to develop an ecology-oriented exploitation mode of groundwater resources. The mode allows the groundwater levels in different zones to be regulated by optimizing groundwater exploitation modes. The prediction results show that the supergene ecological quality will be better in 2020 and even more groundwater can be exploited in this mode. This study provides guidance for regional groundwater management, especially in regions with an obvious water scarcity.

1. Introduction

Groundwater resources is the most important, even the only water supply source in arid and semiarid regions. For a long time groundwater was taken only as a natural recourse and the studies of its ecological attributes were neglected intentionally or unintentionally (Cooper et al., 2006). As groundwater circulation mode and its ecological value have not been well understood in the past, the unreasonable exploitation of water resources altered catchment hydrology and induced a series of environmental problems, such as decline of water level, reduction of spring discharges, degradation of vegetation, soil secondary salinization, and desertification (Stromberg et al., 1996; Rao et al., 2001; Zacharias et al., 2005; Dai and Samper, 2006; Diggelen et al., 2006; Zhu et al., 2007; Dai et al., 2010, 2014; Vasilache et al., 2012; Yang et al., 2014; Bassi et al., 2014). Therefore, a rational or optimal groundwater exploitation mode is needed for addressing the above-listed ecological environment issues.

In recent years, the advancement of the ecological hydrology provides valuable insights for conceptually understanding of the role of groundwater in supergene ecosystem (Kløve et al., 2011; Bormann et al., 2012; Kong et al., 2005; Han et al., 2013; Shang et al., 2014; Lu et al., 2015; Hu et al., 2016). Numerous studies have shown that there is an obvious correlation between groundwater depth and ecological status (Cooper et al., 2006; Jin et al., 2007; Kopeć et al., 2013; Shafroth et al., 2000; Tian et al., 2015; Zhang et al., 2015; Zhu et al., 2015a) and groundwater level is one of the major factors that affects the ecological type (Froend and Sommer, 2010; Zhang et al., 2012; Zhu et al., 2015b). A better understanding of the interaction between groundwater and vegetation has been obtained by ecology-hydrology models or environmental tracer studies during the water-level fluctuating processes (Cheng et al., 2011; Chui et al., 2011; Jeevarathinam et al., 2013; Karimov et al., 2014; Karunasingha et al., 2013; Milzow et al., 2010; Xin et al., 2013; Wang et al., 2013; Zhu et al., 2016). The concept of the groundwater-ecological value was studied by Wang et al. (2004), in which they derived the groundwater threshold values for protecting the dependent ecosystems and evaluating groundwater resources.

Northwest China is one of the driest regions in the world (Shi and Zhang, 1995). As many other arid and semi-arid regions, this region has experienced increased groundwater exploitation and degraded ecological environment (Cheng et al., 2002; Fang et al.,

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2015; Li et al., 2011; Wang et al., 2012, 2016; Bai et al., 2014; Liu et al., 2015). Previous studies about groundwater and ecological environment have been mainly focused on features and distributions of groundwater resources, as well as the relation between groundwater and ecosystem in a local scale (Wu et al., 2015; Zhu et al., 2015a). There is no study focuses on quantifying groundwater exploitation modes based on the groundwater circulation modes and the relation between groundwater and ecosystem at a regional scale (Luo et al., 2010; Liu et al., 2015; Sun et al., 2015). This study combined field surveys, remote sensing studies, and numerical simulations with ecological assessment models in the northern Tianshan Mountains of Xinjiang, China. The purpose of this study is to quantitatively delineate an ecology-oriented development mode of groundwater resources for evaluating the tradeoff between groundwater development and ecological environment in arid and semiarid regions.

2. Study area

The study area is located in the northern Tianshan Mountains, the southern part of Junggar Basin (Fig. 1), which is bounded by the Ganhezi River to the east, the Guertu River to the west, the Tianshan Mountains to the south, and the Gurbantunggut desert edge to the north. The distance from east to west is 380 km and the width (from south to north) is 80–150 km with a total area of 34,000 km^2. The region is in an arid and semi-arid climate with a mean annual rainfall between 220 mm in the South and 100 mm in the North, approximately 70% occurring in the wet season from June to September. Coinciding with the wet season is high potential evapotranspiration or evaporation and plant transpiration (1300 mm, approximately 61% of annual potential evapotranspiration). There are 14 inland rivers in the study area including the Urumqi River, Hutubi River, Manas River, Kuitun River, etc., which are derived from meteoric water and glacier water in the mountains, flowing northward and draining into the lakes or subducting in the deserts. The area gently slopes from southeast to northwest with an average elevation of 450 m above the sea level, striding across multiple geomorphic types: mountains, alluvial-proluvial fan, alluvial plain, lakes and deserts. Because of the similar depositional environment, each river and the beneath groundwater system are featured by a similar hydrogeological structure from south to north. Along this direction the aquifer laminarity and layers become thinner and the groundwater depth varies from deep to shallow and finally to deep when close to the northern boundary (Qiao et al., 2005).

3. Data collection and methods

3.1. Data collection

Field surveys have been conducted since 2003 in the study area. A total of 188 observing wells were distributed to measure groundwater levels half-monthly. The shallow water-table records were taken for a short time (or periodically) to study the relation between groundwater and vegetation (black solid circles in Fig. 2). Long-term observation data from 45 wells were selected to calibrate and validate the numerical simulation models (green[1] solid circles in Fig. 2).

Three typical profiles were selected for observing the succession of surface vegetation along groundwater flow and vegetation growth in 35 plots with 10 m × 10 m. In the study area, supergene ecological transformation in four periods was detected by interpreting multi-spectral Landsat MSS/TM.ETM imagery of 1:100,000 acquired on August 1973, September 1990, August 2000 and September 2009. The spatial analysis for supergene ecological dynamics was finished by the use of ESRI ARCGIS 9.3 (ESRI, 2008).

3.2. Groundwater flow model

In the study area, a single super-thick aquifer composed mainly of loose gravel and sand lies in the alluvial-proluvial fan, while a multilayer aquifer system alternated with sand and clay is located in the alluvial plain. The groundwater in the porous sediments is assumed to be a linear Darcy flow. Precipitation and snow-melt water in the southern mountain area are the major recharge sources for groundwater in this area. The groundwater discharges in forms of evapotranspiration, spring, lateral flow and groundwater abstraction while flowing to near the north boundary. Based on mass conservation and energy conservation law, the groundwater flow equation in the study area is expressed as (Dai and Samper, 2004):

$$\nabla \cdot (K\nabla h) - \sum_{i=1}^{m} Q_i \delta_i = S_s \frac{\partial h}{\partial t} \quad (1)$$

where h represents the hydraulic head (m) at spatial coordinates (x, y and z), K is the hydraulic conductivity (m/d), m is the number of wells; S_s is specific storability (1/m), Q_i is the flow rate of the i^{th} well, δ_i is Dirac function for the i^{th} well, and t is time (d).

The finite difference method was applied for solving above mathematical Eq. (1) numerically. The numerical model was calibrated and validated by trial and error method to define the major model parameters, such as hydraulic conductivity, specific storage and specific yield. The calibration processes obtained a reasonable good match between simulated and observed hydraulic heads in 45 observation wells. About 74% of the observation wells have an averaging absolute head error less than 0.5 m and 92% of the wells have an error less than 1 m. The fitting results from four wells (whose locations are shown in Fig. 2) are presented in Fig. 3. The fitting results indicate that both of the observed and simulated heads have a similar variation trend although the simulated groundwater heads have smaller variation amplitude than the measured heads. Overall, the developed groundwater-flow model shows a higher simulating accuracy and may reasonably reflect the groundwater circulation in the study area.

3.3. Ecological assessment model

In this study, the assessment of supergene ecological effects induced by groundwater-level fluctuation was conducted using comprehensive index method. A supergene ecological index (SEI, dimensionless) was evaluated using the following formulas (Li et al., 2005):

$$SEI = \sum_{i=1}^{n} Y_i \times G_i \quad (2)$$

$$Y_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \times 10 \quad (3)$$

where n is the number of driving factors, G_i is the weight of driving factors, X_i and Y_i are original data of driving factors and their standard values, respectively, and X_{max} and X_{min} are the maximum and minimum of original data, respectively. The driving factors include geology, geomorphology, hydrogeology, which is mainly quantified by groundwater depths and computed numerically from Eq. (1), and hydrometeorology.

[1] For interpretation of color in Figs. 2 and 4, the reader is referred to the web version of this article.

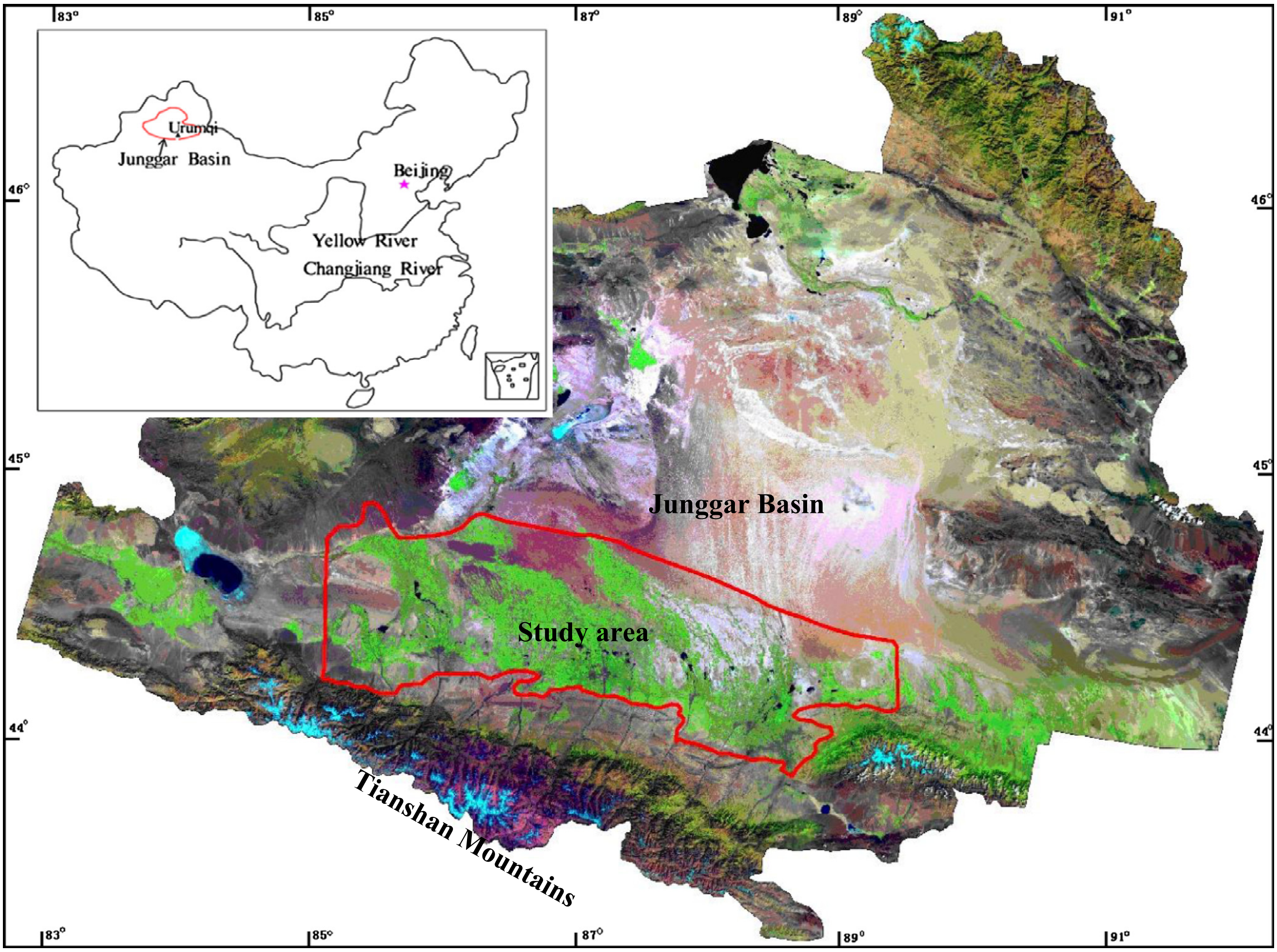

Fig. 1. Location map of the study area (bounded with red line) in China (the horizontal and vertical axes are geographical coordinates). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

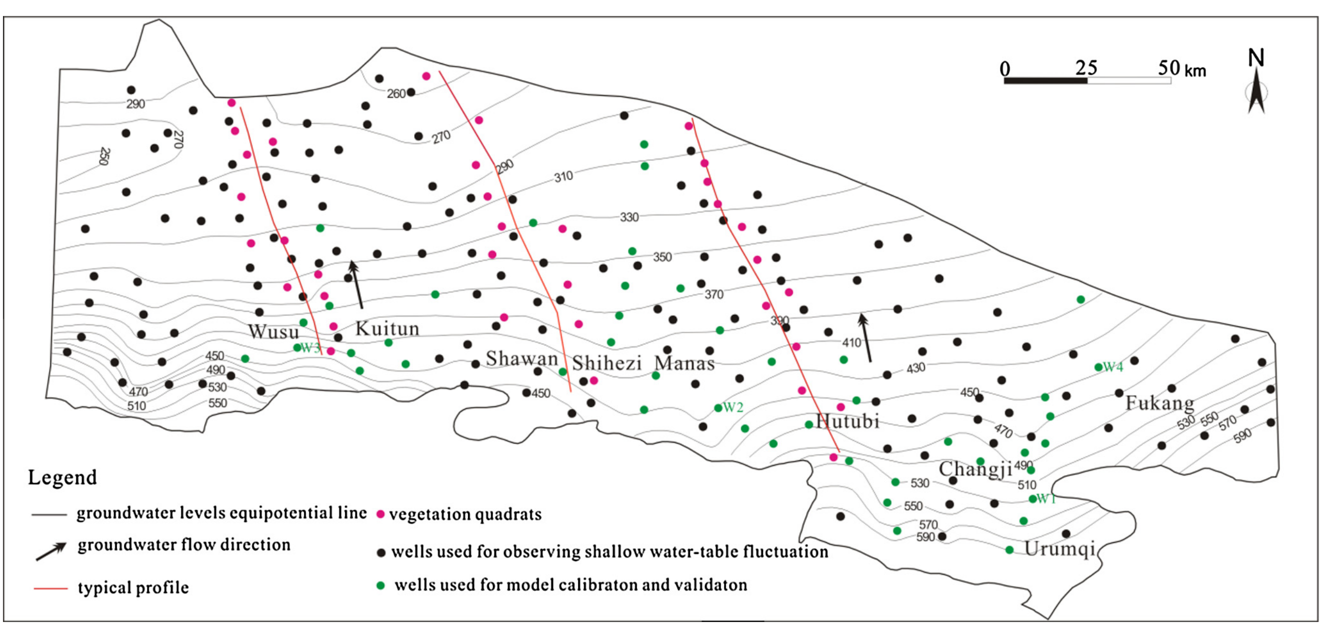

Fig. 2. Sample locations in the study area (the horizontal and vertical axes are geographical coordinates).

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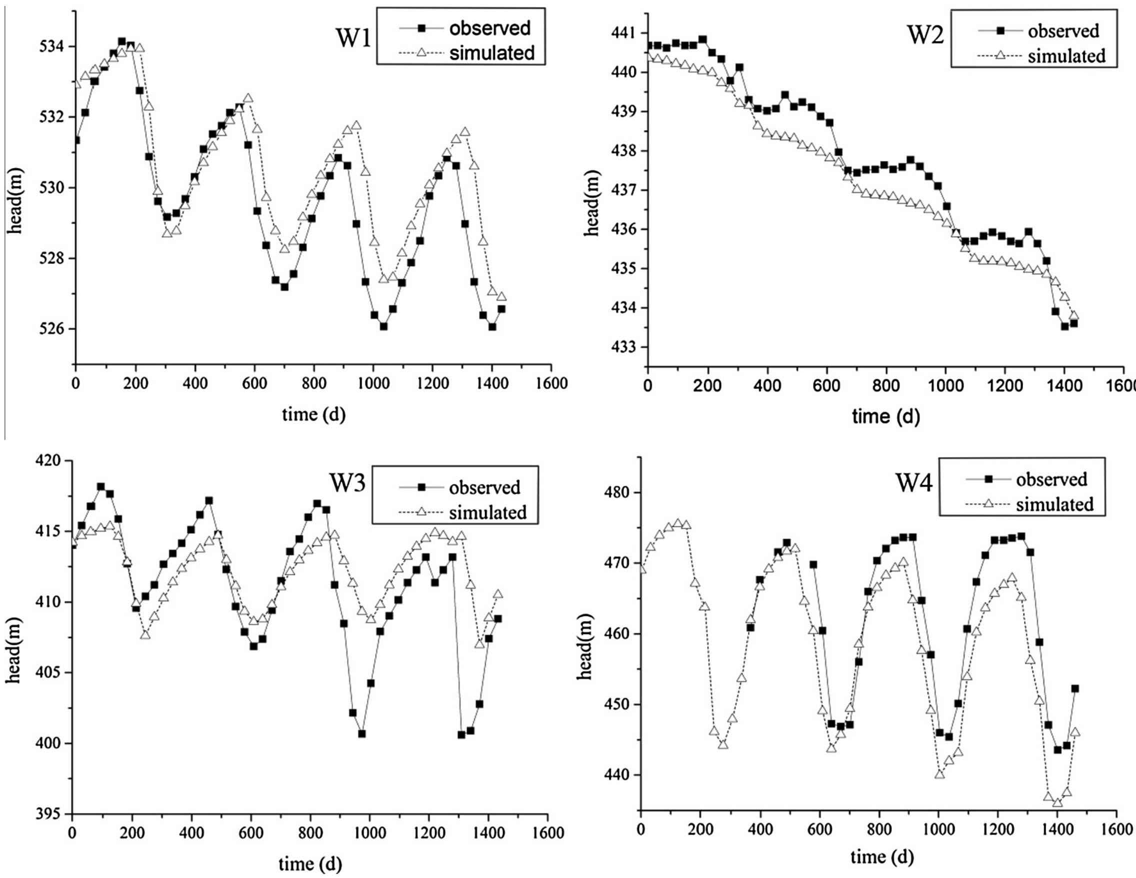

Fig. 3. Observed and simulated groundwater levels of typical observation wells during the validation period.

In order to assess quantitatively the quality of supergene ecology, the SEI (from 1 to 10) was classified into five grades: excellent (1–2), good (3–4), common (5–6), poor (7–8) and very poor (9–10). A higher value indicates a worse supergene ecological quality. More detailed discussions can be found from Li et al. (2005), Zhang et al. (2015); and Zhu et al. (2015a).

4. Results and discussions

4.1. Relations between groundwater and supergene ecology

4.1.1. Groundwater circulation mode

Analysis of groundwater circulation is important when studying an ecology-oriented exploitation mode of groundwater resources because it can provide valuable information about potential threats to both the quantity and quality of the groundwater. Groundwater circulation research is based on the spatial structure of aquifer systems and the runoff features of flow system (Wang et al., 1995); the former determines the evolution of groundwater circulation while the latter controls the strength. Formation, evolution, and exploitation of groundwater resources and ecological environment problems have a great difference from mountains to alluvial-proluvial fan, to alluvial plain, and to lakes or desert. To illustrate the groundwater circulation modes of the study area, a typical profile of groundwater flow along Manas River was simulated (Fig. 4). From mountain to alluvial plain, the hydrogeological structure shows a transitional feature from single layer towards multi layers while the seepage velocity of groundwater indicates an obvious horizontal stratification. According to the magnitude of seepage velocity, hydrodynamic field can be divided into four zones: a strong-runoff zone (1–0.5 m/d), a common-runoff zone (0.5–0.1 m/d), a weak-runoff zone (0.1–0.01 m/d), and a very weak-runoff zone (<0.01 m/d). The strong-runoff zone is located in the alluvial-proluvial fan while the very weak-runoff zone is at the fringes of desert. We can differentiate among three distinct flow systems: local flow system, intermediate flow system and regional flow system (Toth, 1963; Tóth and Almási, 2001). The local flow system (green line in Fig. 4) is often near the surface and occurs over short distances, with characteristics of strong flow velocity and short residence time; intermediate and regional flow systems (blue and red line in Fig. 4, respectively) usually occur at a greater depth and over greater distances with characteristics of a weaker flow velocity and a longer residence time. The hydrodynamic field indicates that recharge takes place in the mountains areas, and water flows into the alluvial plain after multiple transformations between groundwater and surface water in the alluvial-proluvial fan, and finally subducts into the desert, marking the completion of a whole water cycle from the formation zone to transformation zone, to evapotranspiration zone, and to subduction zone.

Above described circulation mode is consistent with previous studies (Li and Hao, 1999; Pan et al., 2003; Huang and Pang, 2010). Moreover, we depicted the natural flow paths, flow field characteristics, and recharge and discharge relationships between groundwater and surface water more comprehensively and quantitatively.

4.1.2. Suitable groundwater depth for supergene ecology

By using the groundwater circulation mode, we characterized the study area with a typical inland arid ecosystem composed of gobi, habitable zone, artificial/natural oasis, and desert. Oases are the essence of ecosystem in arid and semiarid regions and a well-performing oasis ecosystem is an essential precondition for achieving a balance between groundwater development and

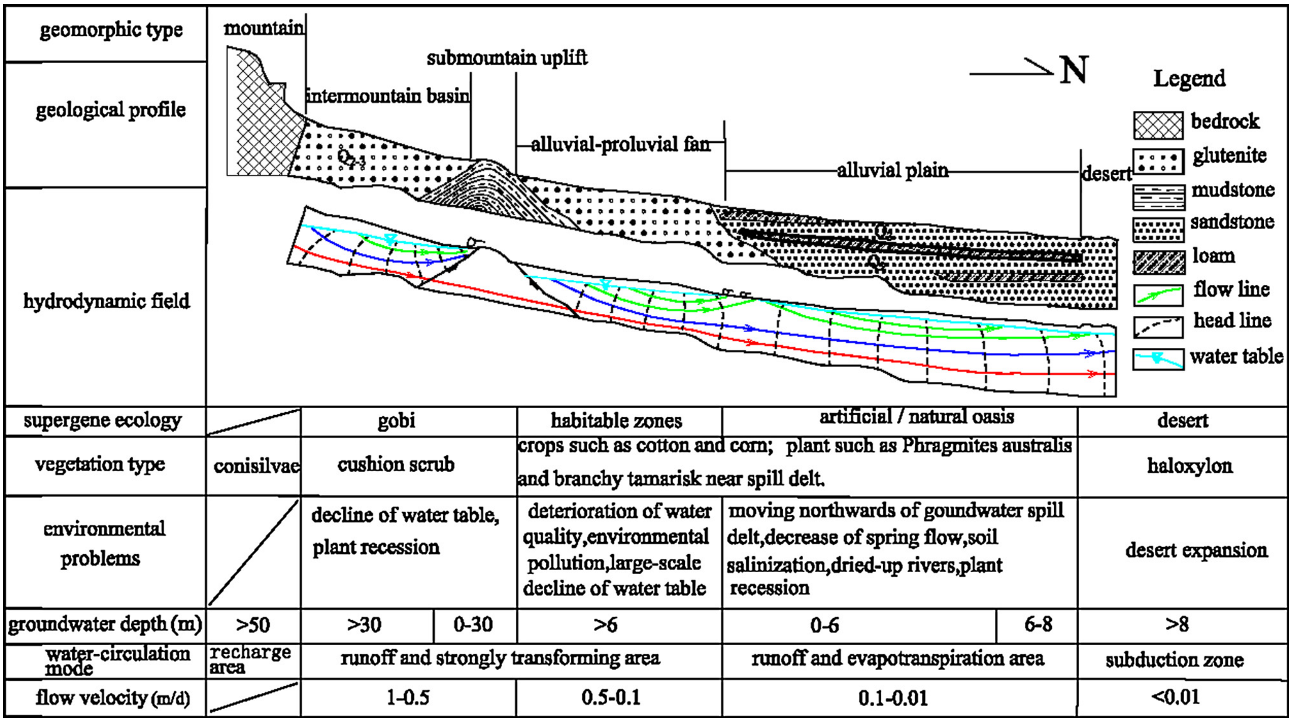

Fig. 4. Water-circulation modes and corresponding supergene ecological effects.

ecosystem. Among many influence factors, groundwater depth is the most important in sustaining the ecological environment of an oasis (Jin et al., 2007; Ye et al., 2009; Zhu et al., 2015a). According to the field surveys and earlier studies (Wang et al., 2001, 2013), soil secondary salinization appeared when groundwater depth was less than 3 m, which further leads to most herbs died, arbors and shrubs withered up, and the land began to be desertification when groundwater depth was between 6 and 8 m; arbors and shrubs degraded, and finally desertification became very serious when groundwater depth was more than 8 m. It suggested that the best suitable groundwater depth for keeping a good supergene ecology was 3–6 m in this area (Wang et al., 2013).

4.1.3. Ecological environment problems

The northern Tianshan Mountains was the most flourishing economic area in the Junggar Basin, with about 69% of water consumption in the entire basin (Deng et al., 2010). Water demand has increased rapidly in recent years with growing population and booming economy. Unreasonable water-resource production has changed the natural distribution of water resources in time and space and destroyed the water-tied ecosystem. In the alluvial-proluvial fan, continuous water-table decline (which leads to reducing of spring flows and shrinking of the northward groundwater spilling belts) occurs by intensively diverting surface water to artificial channels and improving water efficiency of canal systems, as well as irrational groundwater exploitations. For example, in the Manas river valley, the groundwater levels are fallen annually by 0.4–1.1 m, the spring flow is reduced annually by about $494 \times 10^4\ m^3$ (Fig. 5), and the groundwater spilling zone is migrated northward by about 9 km since the 1960s. During year 1980, due to increases in precipitation, the spring flow rate had a rebound and after that time the spring flow rate remained it downward trend. In the alluvial plain, the groundwater depth is higher than the capillary rise height, which is caused by the traditional irrigation such as surface flooding irrigation and local groundwater pumping. Soil salinization becomes a big concern because of the

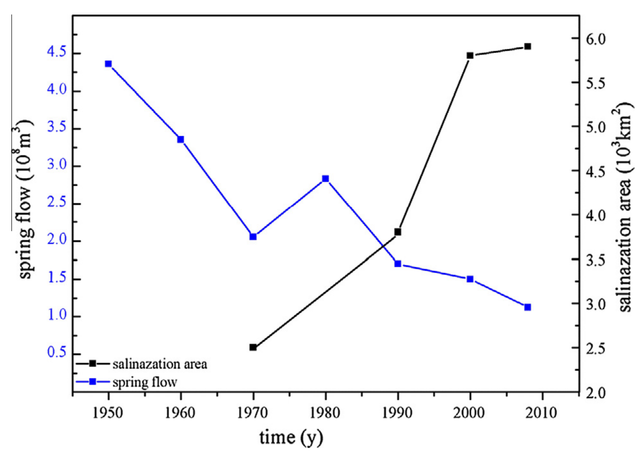

Fig. 5. Measured spring flow rates of the Manas River valley from 1950 to 2008 and the increased area of soil salinization from 1973 to 2009.

accumulation of soluble salt generated by evaporation. Actually, there is an average growth of about 94.4 km^2 per year in salinization according to the results of the remote sensing interpretation from 1973 to 2009 (Fig. 5). At the edge of the deserts, expansion of the deserts and shrinking of lakes and vegetation areas are caused by overuse of water in the upstream. For example, the peak of sand dune advanced by 1–2 m per year in the Urumqi river valley. It is absolutely vital for the ecological environment to regulate naturally groundwater levels within a suitable range. However, in this area the groundwater levels are directly controlled by the exploitation mode of groundwater resources.

4.2. Exploitation mode of groundwater resources

4.2.1. Groundwater exploitation mode

In order to utilize groundwater resources efficiently and rationally, a plan of optional groundwater exploitation should be

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designed based on the local unique hydrogeological characteristics and the interaction among groundwater, surface water, and ecological environment. Five suggestions were presented by Guo et al. (2001) for reasonable groundwater exploitation in the northwest China. Shao et al. (2003) demonstrated the groundwater-exploitation mode in inland basin of northwest China, but the optimized allocation of groundwater recourses was not discussed and the quality of supergene ecology induced by water-level fluctuations was not evaluated quantitatively. In this study, an ecology-oriented exploitation mode of groundwater resources (Fig. 6) is proposed as follows:

(1) Water-conservation exploitation in the piedmont zone: The amount of groundwater exploited in this area is advised to be as little as possible. The piedmont zone including intermountain basin and fan apex is sparsely distributed, where the thick aquifers composed mainly of gravels and sands are natural groundwater reservoirs with a groundwater depth of more than 30 m. Appropriate project measures such as afforestation and dredging sluggish rivers should be taken for an effective utilization of the regulation-storage function of groundwater reservoirs. All these measures are to allow more surface runoff to infiltrate and recharge the aquifers during the rainy season, reducing ineffective evaporation from rivers, canals and reservoirs, and guaranteeing more water to recharge the downstream areas. Note that afforestation and dredging sluggish rivers have the potential to increase the ineffective evaporation and transpiration, but since the groundwater depth is more than 30 m in this zone, the impact or the intensity of the evaporation and transpiration is very limited.
(2) Well-spring conjunctive exploitation in the alluvial-proluvial fan: The plan of well-spring conjunctive exploitation is to increase the amount of water pumped from wells in some extent to reduce the ineffective evaporation from springs. Wells and springs are two ways of groundwater discharge in the alluvial-proluvial fan. There is a relation between groundwater withdrawal from wells and spring flows, as shown in Fig. 7. With the same groundwater recharge, the increased amount of groundwater from wells is more than the reduced amount of spring flows, which means a reduction of ineffective evaporation from springs. Centralized water supply sources are chosen in the middle and margin of the alluvial-proluvial fan to solve the water shortage problems. The groundwater flow should be kept in a stable state in the whole exploiting process.
(3) Shaft irrigating-draining exploitation in the upstream alluvial plain: Irrigation water is advised to be pumped only from wells. Soil salinization is a serious ecological problem in the upstream alluvial plain because the groundwater depth is usually less than 3 m there. Pumping water from wells is of great help to regulate the groundwater depth to a suitable range (3–6 m). Meanwhile, soluble salts are transported downward by the infiltration water to deeper places in the soil. The whole process is just a reverse process of salinization.
(4) Canal-well conjunctive exploitation in the downstream alluvial plain: Most of the water supply is coming from surface water and groundwater is pumped only in dry seasons. In most of the time, the groundwater depth is kept between 3 and 6 m, and sometimes may be more than 6 m when groundwater is pumped during the dry season. Usually groundwater levels begin to recover when the rainy season begins in June.
(5) Decentralized exploitation at the edge of desert: Groundwater is pumped from numerous decentralized wells. Water supply is completely from groundwater since no other reliable resources can be used alternatively. Compared with centralized exploitation, decentralized exploitation from numerous wells can prevent water levels from significantly declining. Desert vegetation can still survive instead of degradation without the significant decline of groundwater levels, which helps to stop desert expansion. Meanwhile, modern irrigating systems should be adopted to reduce the irrigation quota.

4.2.2. Optimized allocation of groundwater resources

At a watershed scale, optimized allocation of water resources is based on the processes of water circulation. A three-dimensional numerical model was established to simulate groundwater flow in the study area. Using the above groundwater-exploitation mode in 2008 and the related hydrogeological data, the calibrated model was employed to forecast the evolution of the groundwater heads from 2009 to 2020. An average precipitation (computed from the observed precipitation data from 1950 to 2008) was used as our model input (Shang et al., 2014). The results of optimal allocation of groundwater resources are shown in Fig. 8. Groundwater sustainable yield was intimately linked with groundwater depth to regulate groundwater levels within a suitable range. The shallower of the groundwater depth, the larger of the groundwater sustainable yield. In the upstream alluvial plain, when groundwater

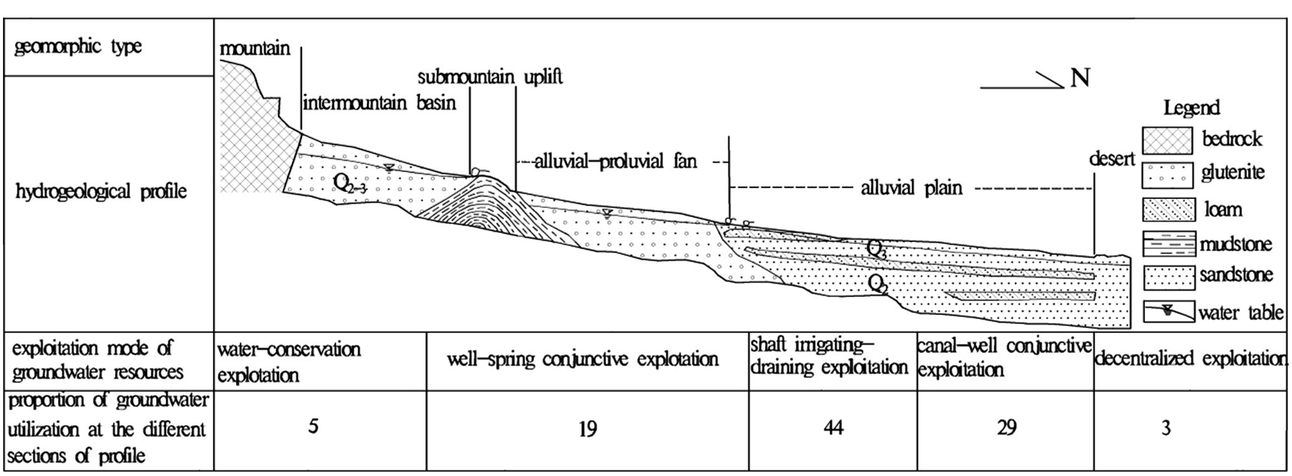

Fig. 6. Exploitation modes of groundwater resources in the study area.

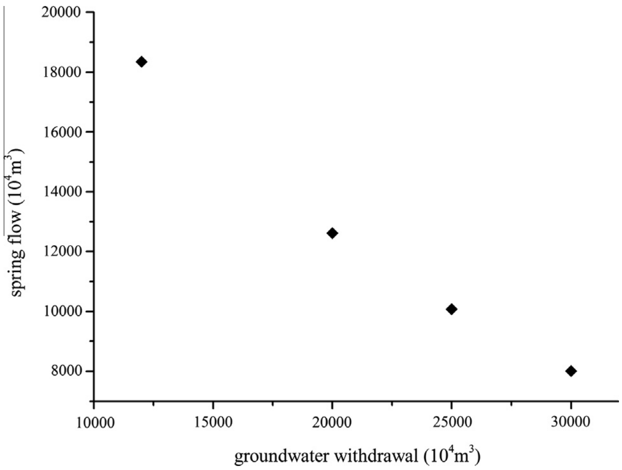

Fig. 7. Relation between groundwater withdrawal and spring flow rates.

Table 1
Weight values of driving factors used to evaluate supergene ecology.

Driving factors		Weight
Geology and geomorphology	Geomorphic type	0.104
	Lithology of the unsaturated soil	0.055
	Structure of the unsaturated soil	0.031
Hydrogeology	Groundwater depth	0.385
	Groundwater mineralization	0.143
	Hydrochemical type of groundwater	0.082
Hydrometeorology	Rainfall	0.1
	Evaporation	0.1

exploitation modulus was between 0.16 and 0.2 $m^3/(m^2·a)$ the depth was less than 1 m; when the modulus was between 0.12 and 0.16 $m^3/(m^2·a)$ the depth range was from 1 to 3 m. In the downstream alluvial plain, when groundwater-exploitation modulus was between 0.04 and 0.06 $m^3/(m^2·a)$ the depth range was from 3 to 5 m; when the modulus was between 0.02 and 0.04 $m^3/(m^2·a)$ the depth range was from 5 to 8 m. In the middle and margin of alluvial-proluvial fan, groundwater-exploitation modulus was between 0.08 and 0.12 $m^3/(m^2·a)$, while it was less than 0.02 $m^3/(m^2·a)$ in the fan apex and at the edge of desert. The numerical simulation results improved the results that obtained by a lumped parameter model (Wang et al., 2001, 2004). Through coupled optimization of groundwater flow simulation and management model with ecological constrains, the exploitation threshold of groundwater resources was computed with a linear programming solver (or a Simplex solver). The maximum (or threshold) groundwater exploitation resources in this area is 22.8×10^8 m^3/a, a 4.4% increase over that of the year 2008, and the proportion of groundwater utilization was 5%, 19%, 44%, 29% and 3% for the piedmont zone, alluvial-proluvial fan, upstream alluvial plain, downstream alluvial plain, and desert edge, respectively (Fig. 8). The evapotranspiration from groundwater is 8.7×10^8 m^3/a, a 14.7% decrease over that of the year 2008, and the increased amount of groundwater exploitation is mainly obtained from the reduced ineffective evaporation.

4.2.3. Assessment of supergene ecological effects

The evolution of supergene ecology is influenced by many driving factors, which include geology, geomorphology, hydrogeology, which mainly quantified by groundwater depths, and hydrometeorology. Analysis hierarchy process (AHP) is designed to deal with complex and multi-factor problems and it is used widely to determine evaluation index weights (Solnes, 2003; Vidal et al., 2011). Here, the AHP is used to analyze the relative importance of each driving factor. According to the principle of AHP, a key step is to construct judgment matrix in order to obtain the greatest eigenvalue and the corresponding eigenvector. Another key step is that consistency test of the judgment matrix must be passed, and finally the weight of each driving factor is obtained (Table 1). For example, "Geology and geomorphology" with a weight of 0.19 is a fundamental factor controlling the spatial distribution of supergene ecology. "Hydrogeology" with a weight of 0.61, especially groundwater depth, is a decisive factor affecting the quality of supergene ecology. "Hydrometeorology" with a weight of 0.2 is an indirect factor impacting supergene ecology through vadose zone and groundwater. Because the exploitation and utilization of groundwater resources could cause a series of supergene

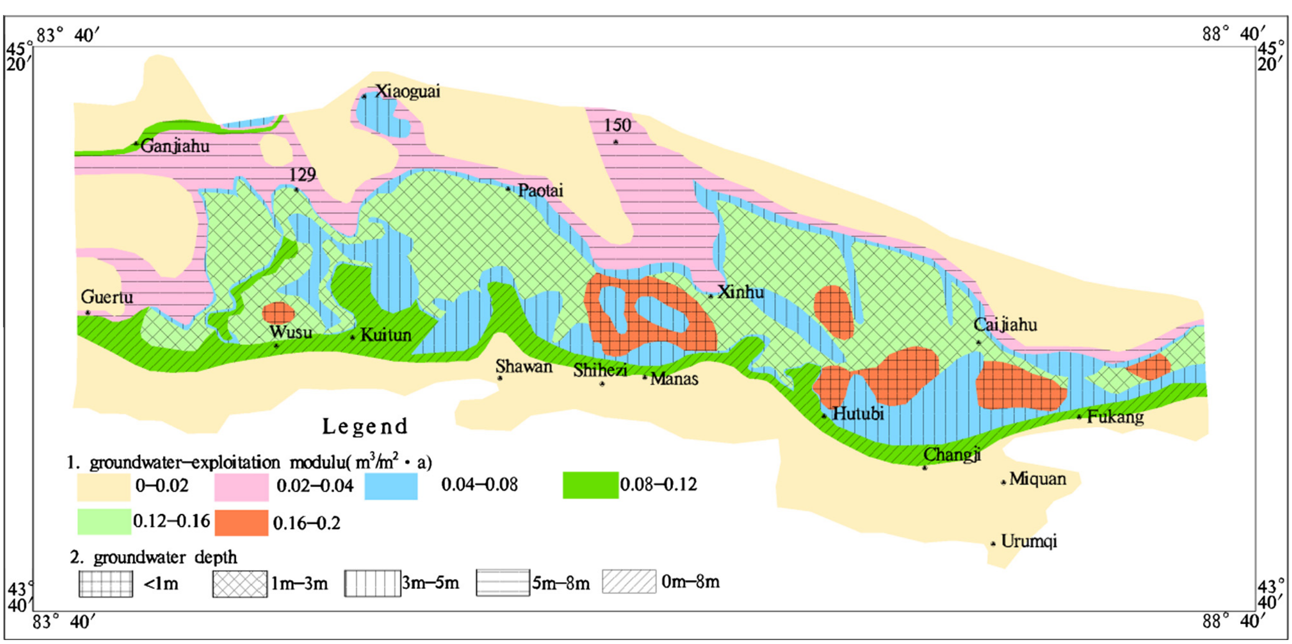

Fig. 8. Distribution of groundwater-exploitation modulus in the study area (the horizontal and vertical axes are geographical coordinates).

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Table 2
Comparison of supergene ecological effects in different exploitation modes.

Evaluation of supergene ecological effects		Excellent	Good	Common	Poor	Very poor
Area/km^2	Current year 2008	1453.2	5709.0	16538.8	5639.8	5259.2
	Current exploitation mode in 2020	519.0	4394.2	16608.0	7266.0	5812.8
	Optimized exploitation mode in 2020	1730.0	6055.0	16988.6	5120.8	4705.6
Percent/%	Current year 2008	4.2	16.5	47.8	16.3	15.2
	Current exploitation mode in 2020	1.5	12.7	48.0	21.0	16.8
	Optimized exploitation mode in 2020	5.0	17.5	49.1	14.8	13.6

ecological effects through a hydrodynamic and hydrogeochemical field, human activities would accelerate the evolution of supergene ecology.

Based on the above driving-factor analysis, comprehensive index method was applied to quantitatively assess the effects of supergene ecology in the current year, and the results (Table 2) were in accordance with the actual conditions (Zhang, 2011). Using the index method, supergene ecological effects were assessed from 2009 to 2020 under the current groundwater-exploitation mode and the optimized groundwater-exploitation mode. The comparison of results was shown in Table 2.

Under the optimized groundwater-exploitation mode, the quality of supergene ecology will be improved in 2020. Compared to that of the year 2008, the area of optimized mode is increased by 0.8% at the excellent supergene ecological quality, 1% at the good, and 1.3% at the common. The area of the poor quality is decreased by 1.5% poor and the very poor is decreased by 1.6%. This outcome definitely illustrates that the optimized exploitation mode can improve the trend from very poor to excellent in the supergene ecological quality. If the current groundwater-exploitation mode continues, the quality of supergene ecology will be worse in 2020. Compared to the year 2008, the area of current mode is decreased by 2.7% at the excellent and 3.8% at the good, and increased by 0.2% at the common, 4.7% at the poor, and 1.6% at the very poor. Thus, it is demonstrated that the current exploitation mode is irrational. The above results indicate, on the other hand, that ecological negative effects induced by human irrational activities spread quickly and widely, but their restoration is comparatively slow. After destruction of the ecosystems, the current treatment or remediation techniques would not work effectively and its cost would be huge. Hence, an ecology-oriented exploitation mode of groundwater resources is instructive for regional water resource management practices, especially for regions with an obvious water scarcity.

5. Summary and conclusions

The following conclusions can be drawn from this study:

1. A three-dimensional groundwater flow model has been established to simulate groundwater flow in the study area and the model was calibrated by using the groundwater-exploitation mode in 2008 and the related hydrogeological data. The calibrated numerical model was employed to forecast the evolution of the groundwater depths from 2009 to 2020. The groundwater depths and other driving factors are connected with the quality of supergene ecology by the ecological assessment model. Therefore, the patterns of supergene ecology are controlled by the formation and evolution of groundwater resources in the study area. There are three patterns of supergene ecology as water moves from formation zone to seduction zone: mountains, oases and deserts.
2. The ecology-oriented exploitation mode of groundwater resources was constructed based on the interaction among surface water, groundwater, and the ecological attributes of groundwater, including water-conservation exploitation in the piedmont zone, well-spring conjunctive exploitation in the alluvial-proluvial fan, shaft irrigating-draining exploitation in the upstream alluvial plain, canal-well conjunctive exploitation in the downstream alluvial plain, and decentralized exploitation at the edge of desert.
3. Through a linear programming solver of the groundwater-ecological management model, the exploitation threshold of groundwater resources has been computed to be 22.8×10^8 m^3/a and the proportion of groundwater utilization was 5%, 19%, 44%, 29% and 3% for piedmont zone, alluvial-proluvial fan, upstream alluvial plain, downstream alluvial plain, and desert edge, respectively.
4. It has been demonstrated that the ecology-oriented exploitation mode of groundwater resources can achieve a tradeoff between groundwater development and ecological environment, but the current mode of groundwater exploitation has induced negative effects of supergene ecology, which would spread quickly and widely, and restore slowly. While comparing to the quality of supergene ecology of the year 2008, the optimized groundwater-exploitation mode will improve it from 2009 to 2020 by increasing the area of the good quality and decreasing the area of the poor quality.

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References

Bai, Y., Xu, H., Ling, H., 2014. Eco-service value evaluation based on eco-economic functional regionalization in a typical basin of northwest arid area, China. Environ. Earth Sci. 71, 3715–3726.
Bassi, N., Kumar, M.D., Sharma, A., Pardha-Saradhi, P., 2014. Status of wetlands in India: a review of extent, ecosystem benefits, threats and management strategies. J. Hydrol. Reg. Stud. 2, 1–19.
Bormann, H., Ahlhorn, F., Klenke, T., 2012. Adaptation of water management to regional climate change in a coastal region – hydrological change vs. community perception and strategies. J. Hydrol. 454–455, 64–75.
Cheng, D.H., Wang, W.K., Chen, X.H., Hou, G.C., Yang, H.B., Li, Y., 2011. A model for evaluating the influence of water and salt on vegetation in a semi-arid desert region northern China. Environ. Earth Sci. 64 (2), 337–346.
Cheng, W., Zhou, C., Tang, Q., Yao, Y., Zhang, B., 2002. Landscape distribution characteristics of northern foothill belts of Tianshan Mountains. J. Geogr. Sci. 12 (1), 23–28.
Chui, T.F.M., Low, S.Y., Liong, S.-Y., 2011. An ecohydrological model for studying groundwater–vegetation interactions in wetlands. J. Hydrol. 409 (1–2), 291–304.
Cooper, D.J., Sanderson, J.S., Stannard, D.I., Groeneveld, D.P., 2006. Effects of long-term water table drawdown on evapotranspiration and vegetation in an arid region phreatophyte community. J. Hydrol. 325 (1–4), 21–34.

Dai, Z., Samper, J., 2004. Inverse problem of multicomponent reactive chemical transport in porous media: formulation and applications. Water Resour. Res. 40, W074071–W0740718. http://dx.doi.org/10.1029/2004WR003248.
Dai, Z., Samper, J., 2006. Inverse modeling of water flow and multicomponent reactive transport in coastal aquifer systems. J. Hydrol. 327, 447–461.
Dai, Z., Keating, E., Gable, C.W., Levitt, D., Heikoop, J., Simmons, A., 2010. Stepwise inversion of a groundwater flow model with multi-scale observation data. Hydrogeol. J. 18, 607–624.
Dai, Z., Keating, E., Bacon, D., Viswanathan, H., Stauffer, P., Jordan, A., Pawar, R., 2014. Probabilistic evaluation of shallow groundwater resources at a hypothetical carbon sequestration site. Sci. Rep. 4, 4006.
Deng, M.J., Zhang, Y., Li, X.Q., 2010. Development trend of water supply and water demand in the north of the Tianshan Mountains in Xinjiang. Arid Land Geogr. 33 (3), 315–423.
Diggelen, R., Middleton, B., Bakker, J., Grootjans, A., Wassen, M., 2006. Fens and floodplains of the temperate zone: present status, threats, conservation and restoration. Appl. Veg. Sci. 9 (2), 157–162.
ESRI, 2008. What is ArcGIS® 9.3? ArcGIS User's Manual, Redlands, California, p. 130. <http://webhelp.esri.com/ARCGISDESKTOP/9.3/pdf/what_is_arcgis.pdf>.
Fang, G., Yang, J., Chen, Y., Xu, C., Maeyer, P.D., 2015. Contribution of meteorological input in calibrating a distributed hydrologic model in a watershed in the Tianshan Mountains, China. Environ. Earth Sci. 74 (3), 2413–2424.
Froend, R., Sommer, B., 2010. Phreatophytic vegetation response to climatic and abstraction-induced groundwater drawdown: examples of long-term spatial and temporal variability in community response. Ecol. Eng. 36 (9), 1191–1200.
Guo, Z.R., Liu, H.T., Zhu, Y.H., 2001. Study on exploitation and protection of groundwater in Northwestern China. J. Hydraul. Eng. 1, 37–40.
Han, Q., Luo, G., Li, C., Ye, H., Chen, Y., 2013. Modeling grassland net primary productivity and water-use efficiency along an elevational gradient of the Northern Tianshan Mountains. J. Arid Land 5 (3), 354–365.
Hu, Y., Lu, Y.H., Edmonds, J.W., Liu, C., Wang, S., Das, O., Liu, J., Zheng, C., 2016. Hydrological and land use control of watershed exports of DOM in a large arid river basin in Northwestern China. J. Geophys. Res.: Biogeosci. http://dx.doi.org/10.1002/2015JG003082 (on line).
Huang, T., Pang, Z., 2010. Changes in groundwater induced by water diversion in the Lower Tarim River, Xinjiang Uygur, NW China: evidence from environmental isotopes and water chemistry. J. Hydrol. 387 (3–4), 188–201.
Jeevarathinam, C., Rajasekar, S., Sanjuán, M.A.F., 2013. Vibrational resonance in groundwater-dependent plant ecosystems. Ecol. Complex. 15, 33–42.
Jin, X., Wan, L., Zhang, Y., Xue, Z., Yin, Y., 2007. A study of the relationship between vegetation growth and groundwater in the Yinchuan Plain. Earth Sci. Front. 14 (3), 197–203.
Karimov, A.K., Šimůnek, J., Hanjra, M.A., Avliyakulov, M., Forkutsa, I., 2014. Effects of the shallow water table on water use of winter wheat and ecosystem health: implications for unlocking the potential of groundwater in the Fergana Valley (Central Asia). Agric. Water Manage. 131, 57–69.
Karunasingha, D.S.K., Chui, T.F.M., Liong, S.Y., 2013. An approach for modelling the effects of changes in hydrological environmental variables on tropical primary forest vegetation. J. Hydrol. 505, 102–112.
Kløve, B., Ala-aho, P., Bertrand, G., Boukalova, Z., Ertürk, A., Goldscheider, N., 2011. Groundwater dependent ecosystems. Part I: hydroecological status and trends. Environ. Sci. Policy 14 (7), 770–781.
Kong, J.L., Wang, W.K., Zhao, C., 2005. Analysis on the relations between water resources and ecological environment in the Hexi Corridor. Arid Land Geogr. 28 (5), 581–587.
Kopeć, D., Michalska-Hejduk, D., Krogulec, E., 2013. The relationship between vegetation and groundwater levels as an indicator of spontaneous wetland restoration. Ecol. Eng. 57, 242–251.
Li, W.P., Hao, A.B., 1999. Formation and evolution mode of groundwater and its meaning in arid basin of inland, NW China. Hydrogeol. Eng. Geol. 4, 28–32.
Li, S.N., Zhao, Y.Z., Shi, P.J., 2005. Method and application of ecological security analysis in Tibet Plateau – a case study in Qusum County. Res. Soil Water Conserv. 12 (6), 142–146.
Li, W., Liu, Z., Guo, H., Li, N., Kang, W., 2011. Simulation of a groundwater fall caused by geological discontinuities. Hydrogeol. J. 19 (6), 1121–1133.
Liu, X., Shen, Y., Guo, Y., Li, S., Guo, B., 2015. Modeling demand/supply of water resources in the arid region of northwestern China during the late 1980s to 2010. J. Geogr. Sci. 25 (5), 573–591.
Lu, Z., Zou, S., Xiao, H., Zheng, C., Yin, Z., Wang, W., 2015. Comprehensive hydrologic calibration of SWAT and water balance analysis in mountainous watersheds in northwest China. Phys. Chem. Earth, Parts A/B/C 79, 76–85.
Luo, G., Feng, Y., Zhang, B., Cheng, W., 2010. Sustainable land-use patterns for arid lands: a case study in the northern slope areas of the Tianshan Mountains. J. Geogr. Sci. 20 (4), 510–524.
Milzow, C., Burg, V., Kinzelbach, W., 2010. Estimating future ecoregion distributions within the Okavango Delta Wetlands based on hydrological simulations and future climate and development scenarios. J. Hydrol. 381 (1–2), 89–100.
Pan, S.B., Jing, W.Z., Ping, C.L., 2003. Groundwater circulation and evolution model and its sustainable utilization in inland basins of northwest of China. Geogr. Geo-Inform. Sci. 19 (1), 51–54.
Qiao, X.Y., Wang, W.K., Chen, Y., Wang, J., Han, J.P., Liang, X.F., 2005. Storage water structure modes and water cycle characteristic on Tianshan Mountain foot. J. Earth Sci. Environ. 27 (3), 33–37.
Rao, P.B., Subrahmanyam, K., Dhar, R.L., 2001. Geo-environmental effects of groundwater regime in Andhra Pradesh, India. Environ. Geol. 40 (4–5), 632–642.
Shafroth, P.B., Stromberg, J.C., Patten, D.T., 2000. Woody riparian vegetation response to different alluvial water table regimes. West. North Am. Nat. 60 (1), 66–76.
Shang, H., Wang, W., Duan, L., Li, Q., Huo, C., 2014. The optimized allocation of groundwater resources for supergene ecology in the northern foot of Tianshan Mountain. J. Earth Environ. 5 (3), 221–226. http://dx.doi.org/10.7515/JEE201403006 (in Chinese).
Shao, J.L., Cui, Y.L., Li, C.J., 2003. Study on groundwater resource analyses and development in Manas plain. Arid Land Geogr. 26 (1), 6–11.
Shi, Y., Zhang, X., 1995. The influence of climate changes on the water resources in arid areas of northwest China. Sci. Chin. (Ser. B) 25, 968–977.
Solnes, J., 2003. Environmental quality indexing of large industrial development alternatives using AHP. Environ. Impact Assess. Rev. 23 (3), 283–303.
Stromberg, J., Tiller, R., Richter, B., 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona. Ecol. Appl. 6 (1), 113–131.
Sun, C., Li, W., Chen, Y., Li, X., Yang, Y., 2015. Isotopic and hydrochemical composition of runoff in the Urumqi River, Tianshan Mountains, China. Environ. Earth Sci. 74 (2), 1521–1537.
Tian, Y., Zheng, Y., Zheng, C., Xiao, H., Fan, W., Zou, S., Wu, B., Yao, Y., Zhang, A., Liu, J., 2015. Exploring scale-dependent ecohydrological responses in a large endorheic river basin through integrated surface water-groundwater modeling. Water Resour. Res. 51 (6), 4065–4085.
Toth, J., 1963. A theoretical analysis of groundwater flow in small drainage basins. J. Geophys. Res. 68 (16), 4795–4812.
Tóth, J., Almási, I., 2001. Interpretation of observed fluid potential patterns in a deep sedimentary basin under tectonic compression: Hungarian Great Plain, Pannonian Basin. Geofluids 1 (1), 11–36.
Vasilache, V., Filote, C., Cretu, M.A., Sandu, I., Coisin, V., Vasilache, T., et al., 2012. Monitoring of groundwater quality in some vulnerable areas in Botosani County for nitrates and nitrites based pollutants. Environ. Eng. Manage. J. 11 (2), 471–479.
Vidal, L.A., Marle, F., Bocquet, J.C., 2011. Using a Delphi process and the Analytic Hierarchy Process (AHP) to evaluate the complexity of projects. Expert Syst. Appl. 38 (5), 5388–5405.
Wang, D.C., Zhang, R.Q., Shi, Y.H., Xu, S.Z., Yu, Q.C., Liang, X., 1995. General Hydrogeology. Geological Publishing House, Beijing, pp. 87–99 (in Chinese).
Wang, W.K., Wang, Z., Kong, J.L., Yang, Z.Y., Zhao, C., 2001. The distribution characteristics and patterns of rational exploitation/utilization of water resources in Guanzhong Region. J. Nat. Resour. 16 (6), 499–504.
Wang, W.K., Han, J.P., Zhao, Y.Q., Yu, D.M., Wang, H.Y., 2004. Optimal allocation of water resources in Yinchuan Plain. Resour. Sci. 26 (2), 36–45.
Wang, W.K., Dai, Z., Li, J., Zhou, L., 2012. A hybrid Laplace transform finite analytic method for solving transport problems with large Peclet and Courant numbers. Comput. Geosci. 49, 182–189.
Wang, W.K., Yang, Z.Y., Kong, J.L., Cheng, D.H., Duan, L., Wang, Z.F., 2013. Ecological impacts induced by groundwater and their thresholds in the arid areas in Northwest China. Environ. Eng. Manage. J. 12 (7), 1497–1507.
Wang, W.K., Dai, Z., Zhao, Y., Li, J., Duan, L., Wang, Z., Zhu, L., 2016. A quantitative analysis of hydraulic interaction processes in stream-aquifer systems. Sci. Rep. 6, 19876.
Wu, B., Zheng, Y., Wu, X., Tian, Y., Han, F., Liu, J., Zheng, C., 2015. Optimizing water resources management in large river basins with integrated surface water-groundwater modeling: a surrogate-based approach. Water Resour. Res. 51 (4), 2153–2173.
Xin, P., Kong, J., Li, L., Barry, D.A., 2013. Modelling of groundwater–vegetation interactions in a tidal marsh. Adv. Water Resour. 57, 52–68.
Yang, C., Dai, Z., Romanak, K., Hovorka, S., Trevino, R., 2014. Inverse modeling of water-rock-CO_2 batch experiments: implications for potential impacts on groundwater resources at carbon sequestration sites. Environ. Sci. Technol. 48, 2798–2806.
Ye, Z.X., Chen, Y.N., Li, W.H., Yan, Y., Wan, J.H., 2009. Groundwater fluctuations induced by ecological water conveyance in the lower Tarim River, Xinjiang, China. J. Arid Environ. 73 (8), 726–732.
Zacharias, I., Dimitriou, E., Koussouris, T., 2005. Integrated water management scenarios for wetland protection: application in Trichonis Lake. Environ. Model. Softw. 20 (2), 177–185.
Zhang, A., Zheng, C., Wang, S., Yao, Y., 2015. Analysis of streamflow variations in the Heihe River Basin, northwest China: trends, abrupt changes, driving factors and ecological influences. J. Hydrol. Reg. Stud. 3, 106–124.
Zhang, J., 2011. Supergene Ecological Effect and Evaluation Excited by Groundwater Level – Taking the Northern Foot of Tianshan Mountain as an Example Master Thesis. Chang'an University, Xi'an, Shaanxi, China.
Zhang, Q., Xu, H., Li, Y., Fan, Z., Zhang, P., Yu, P., Ling, H., 2012. Oasis evolution and water resource utilization of a typical area in the inland river basin of an arid area: a case study of the Manas River valley. Environ. Earth Sci. 66, 683–692.
Zhu, G.F., Li, Z.Z., Su, Y.H., Ma, J.Z., Zhang, Y.Y., 2007. Hydrogeochemical and isotope evidence of groundwater evolution and recharge in Minqin Basin, Northwest China. J. Hydrol. 333 (2–4), 239–251.
Zhu, L., Gong, H., Dai, Z., Xu, T., Su, X., Li, X., 2015a. An integrated assessment of the impact of precipitation and groundwater on vegetation growth in arid and semiarid areas. Environ. Earth Sci. 74, 5009–5021.
Zhu, L., Gong, H.L., Li, X., Wang, R., Chen, B., Dai, Z., Teatini, P., 2015b. Land subsidence due to groundwater withdrawal in the northern Beijing plain, China. Eng. Geol. 193, 243–255.
Zhu, L., Dai, Z., Gong, H., Gable, C., Teatini, P., 2016. Statistic inversion of multi-zone transition probability models for aquifer characterization in alluvial fans. Stochast. Environ. Res. Risk Assess. http://dx.doi.org/10.1007/s00477-015-1089-2.