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REPORT

Evolution of the groundwater system under the impacts of human activities in middle reaches of Heihe River Basin (Northwest China) from 1985 to 2013

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Abstract Investigation of the evolution of the groundwater system and its mechanisms is critical to the sustainable management of water in river basins. Temporal and spatial distributions and characteristics of groundwater have undergone a tremendous change with the intensity of human activities in the middle reaches of the Heihe River Basin (HRB), the second largest arid inland river basin in northwestern China. Based on groundwater observation data, hydrogeological data, meteorological data and irrigation statistical data, combined with geostatistical analyses and groundwater storage estimation, the basin-scaled evolution of the groundwater levels and storage (from 1985 to 2013) were investigated. The results showed that the unbalanced allocation of water sources and expanded cropland by policy-based human activities resulted in the over-abstraction of groundwater, which induced a general decrease in the water table and groundwater storage. The groundwater level has generally fallen from 4.92 to 11.49 m from 1985 to 2013, especially in the upper and middle parts of the alluvial fan (zone I), and reached a maximum depth of 17.41 m. The total groundwater storage decreased by 177.52×10^8 m^3; zone I accounted for about 94.7 % of the total decrease. The groundwater balance was disrupted and the groundwater system was in a severe negative balance; it was noted that the groundwater/surface-water interaction was also deeply affected. It is essential to develop a rational plan for integration and management of surface water and groundwater resources in the HRB.

Keywords Groundwater/surface-water relations · Human activities · China · Groundwater level · Kriging

Introduction

Groundwater represents the largest stock of accessible freshwater and accounts for about one-third of freshwater withdrawals globally (Siebert et al. 2010; Famiglietti 2014; Gorelick and Zheng 2015). Increasing population numbers, expanding areas of irrigated agriculture and economic development are drivers for an ever-increasing demand for water worldwide (Wada et al. 2010). Consequences of groundwater overdevelopment are becoming increasingly evident, as hydraulic heads drop, and well depths and pumping lifts increase with a consequent rise in production costs, and in some cases water quality can diminish as less desirable deep groundwater is produced (Gorelick and Zheng 2015). Examples of regions experiencing recurrent water stress are North Africa, South Africa, the Central US, Australia, Middle East, Sahel, India, Pakistan, South and Central Asia, North-East China, and localized areas throughout the world (Konikow and Kendy 2005; Hanasaki et al. 2008). The most common symptom is secular decline in water tables and aquifer storage depletion. The Nubian aquifer has experienced 60 m of drawdown in parts of Egypt (Gleeson et al. 2010). Wada et al. (2010) estimate the total global groundwater depletion to have increased from 126 (±32) km^3 year^{-1} in 1960 to 283 (±40) km^3 year^{-1} in 2000 from sub-humid to arid areas.

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In China, especially in the arid and semi-arid inland river basins in northwest China, water resources are not only valuable for human usage, but they are also an important environmental factor due to low precipitation and the dry climate (Ma et al. 2005). Human activities, in particular, large-scale water resources exploitation and development associated with dramatic well-irrigated agriculture and water scarcity in the last decades, has led to tremendous changes in the water regime. The most pressing problem in managing inland rivers is water-use conflicts between the upper, middle, and lower reaches (Xiao et al. 2015). In the lower reaches of the Shiyang River Basin, China, there has been widespread groundwater-level decline by 3–16 m, with a maximum decline of 45 m (Ji et al. 2006). In the Heihe River Basin (HRB), more than 68.1 % of the total water resources in the HRB have been used by the middle reaches; its water resources utilization is at 119.9 % (Lan et al. 2002). Overuse of water has caused the lower reaches to dry up and has accelerated the degradation of the ecological environment; thus, the government implemented the Ecological Water Transfer Project (EWTP) in 2001. Water resources diverted to the lower reaches increased, and downward trends of land degradation and ecological deterioration were alleviated (Zhang et al. 2011). In the middle reaches, however, the amount of water diverted from the Heihe River decreased from 10.4×10^8 m^3 $year^{-1}$ in 1990s to 8.0×10^8 m^3 $year^{-1}$ in 2010 (Nian et al. 2014). Water diversion has induced a "policy-based" water scarcity, and the abstraction of groundwater for irrigation intensified drastically from 0.56×10^8 m^3 $year^{-1}$ in the 1980s to 4.97×10^8 m^3 $year^{-1}$ in 2010. Overexploitation of groundwater resources combined with extensive use of surface water has led to aquifer storage depletion and groundwater level drawdown, springs drying up, and groundwater quality deterioration (Wang et al. 1999; Tang and Zhang 2001; Ding and Zhang 2002; Liu et al. 2002; Wen et al. 2007), and the temporal and spatial distribution of the groundwater system has changed. Meanwhile water use conflicts between the middle and the lower reaches of the HRB remain unresolved.

Groundwater plays an important role in sustaining the local ecosystem and populations in arid and semiarid areas (Schmidt et al. 2013; Simpson et al. 2013; Yin et al. 2013). It is used to irrigate more than 40 % of the farmland and supplies approximately 70 % of the drinking water in the dry northern and northwestern regions of China (Qiu 2010). In the HRB, numerous studies have been undertaken, mainly focused on land-use change and its environmental impacts (Lu et al. 2003; Wang et al. 2007; Qi and Luo 2006; Feng et al. 2013), water resources exploitation, relationships between local economic development and water resource management (Fang et al. 2007; Cai et al. 2014), and water environment changes (Qi and Luo 2005; Ji et al. 2006; Qi and Luo 2007; Zhu et al. 2008; Zhou et al. 2013). However, insights regarding long-term groundwater dynamics for the whole middle reaches of HRB are often ignored. The long-term trends can reflect the gradual natural or man induced changes that are occurring in the system over time (Bajesh et al. 2005). Some studies on groundwater level and storage change before and after the EWTP are available (Yang and Wang 2005; Wei et al. 2008; Hu and Lu 2009; Li et al. 2014), but they are mainly centered on the Zhangye Basin for the short and medium-term. Eastern Jiuquan Basin in the west and Maying Basin in the east have no related studies. This is especially true for the Maying Basin, a region with scarce hydrological observation datasets. Groundwater level and storage measurement is a direct instrument for investigation of the dynamic behavior of groundwater systems. Many studies have used GRACE (the Gravity Recovery and Climate Experiment) gravity satellite data to understand groundwater change (Chinnasamy and Agoramoorthy 2015; Cao et al. 2015), but it is a better fit for large-scaled regions. The water balance methods, geostatistical methods and groundwater models are the commonly used tools to estimate the groundwater storage, and geostatistical methods have been used widely as a convenient tool to make decisions on the management of groundwater levels. Therefore, the Ordinary Kriging method is applied to analyze the spatial and temporal variations of groundwater level fluctuations in this study.

Understanding the behavior of the groundwater body and its long-term trends is essential for making any management decision in a given watershed (Bajesh et al. 2005). Investigation of groundwater renewability in the middle reaches of the HRB by isotopic methods showed that shallow groundwater renewal rates range from 0.01 to 2.5 % of the aquifer volume, while in the deep confined aquifer (below 100 m), the mean annual groundwater renewal rate is less than 0.8 % of the aquifer volume (Nie 2004). Owing to the low groundwater renewability, groundwater resources may be depleted someday because of excess abstraction. Based on geostatistics, this study aims to make a comprehensive analysis on the long-term temporal and spatial variations of the groundwater level and storage in the large-scale middle reaches of the HRB and explores how human activities have affected the groundwater system evolution of the Gobi Desert's artificial oasis system over the last three decades. This work will help to acquire a deeper knowledge and insight on the groundwater system, and to better understand the behavior of the groundwater body and its long-term trends, which are essential for sustainable water management in a large basin. Conflicts between agricultural productivity and environmental health could also possibly be resolved (Wu et al. 2015).

Study area and hydrogeological setting

The middle reaches of the HRB, a Gobi Desert artificial oasis composition system, as showed in Fig. 1, is located in the arid and semi-arid inland region of northwestern China. It is a

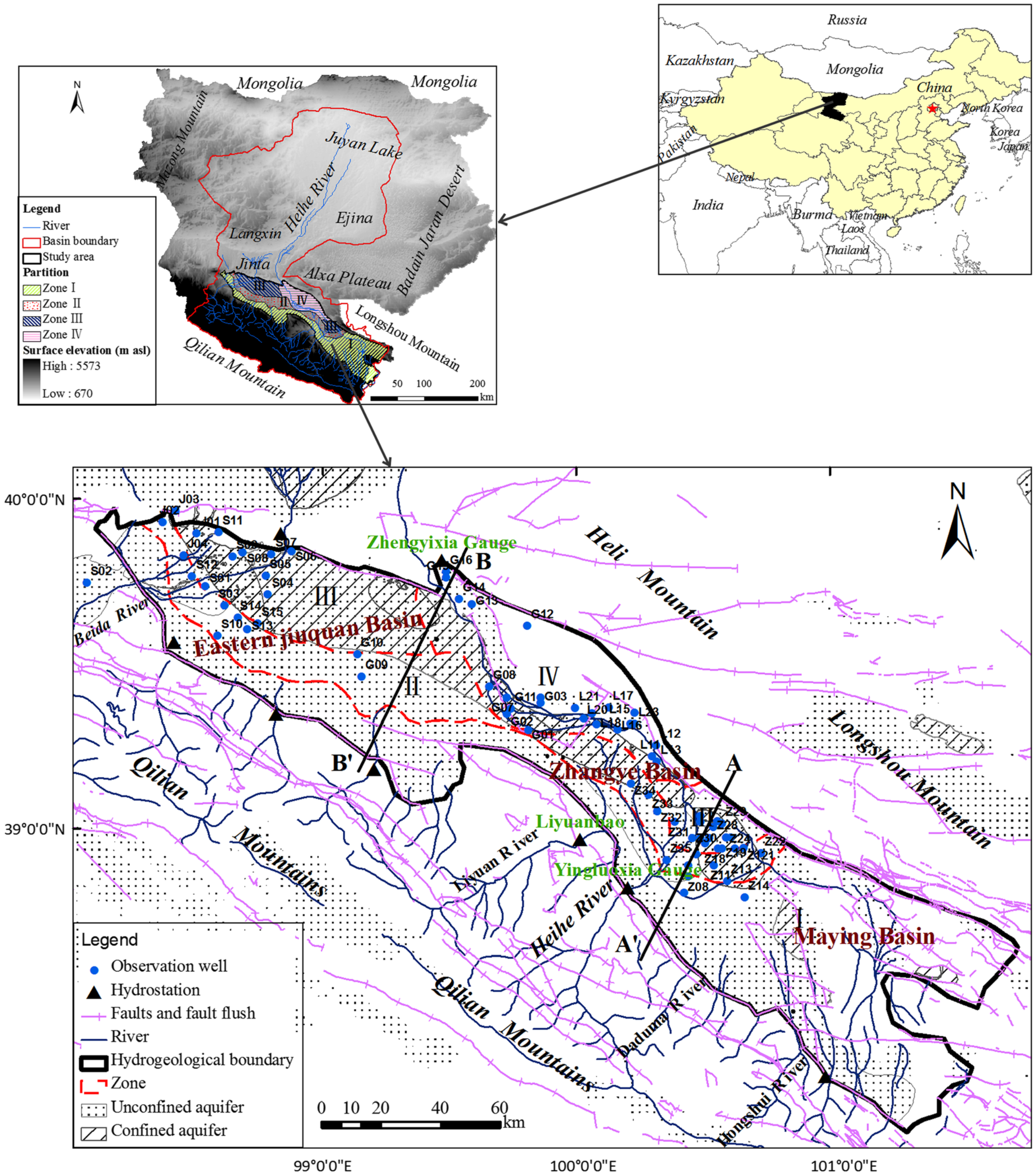


Fig. 1 Hydrogeological conditions and distribution of observation wells of study area; the four partition zones numbered *I* to *IV* from *south* to *north* are: upper and middle part of the alluvia fan, bottom of the alluvial fan, fine soil plain and valley plain

sedimentary basin bounded by the Qilian Mountains to the south, the Heli Mountain and Longshou Mountain to the north, the Jiayuguan Great Faults to the west, and Dahuangshan Mountain to the east. It contains the Zhangye, Eastern Jiuquan and Maying basins (from west to east) with a total area of about 17,050 km^2 (hydrogeological boundary). This region has a continental arid climate with cold winters and hot summers (mean annual lowest and highest air temperature is −27 and 39.1 °C in January and August, respectively) and a mean annual air temperature of 7.6 °C. The mean annual precipitation is 120 mm, about 60 % of which falls from July to September, while only 3 % falls during winter. Mean annual potential pan evaporation is 2,360 mm, and the drying index is 15.9 (Zhao et al. 2010), and elevation ranges from 1,280 to 2,800 m. There are 35 perennial tributaries that enter this area from the Qilian Mountains (as rainfall runoff and snowmelt water) with an average runoff volume of 37.78×10^8 m^3 year^{-1} (Zhou et al. 2011). The Heihe River is the largest one with a total length of 821 km and a runoff volume of 16.0×10^8 m^3 year^{-1}, which accounts for nearly half of the total runoff volume of all the rivers in the basin. It goes through Yingluoxia on the south edge and out of

Zhengyixia on the north edge of the middle reaches and then enters the lower reaches. The upstream and downstream runoffs of the middle reaches are monitored at the Yingluoxia Gorge and the Zhengyixia Gorge stations, respectively. As a highly developed irrigated area, 82.6 % of the region contains developed irrigated agriculture, and the total water consumption is about 25.9×10^8 m^3 $year^{-1}$, of which more than 95.0 % is utilized for agricultural irrigation (Ding and Zhang 2002).

The hydrogeology condition in the middle reaches of the HRB varies from south to north. The southern part of the basin is an area of extensive faulting, underlain by bedrock. A NW–SE thrust fault is present along the foot of the Qilian Mountains. Down-faulted bedrock (pediments) extends toward the northeast, overlain by Quaternary sediments. The uplift of the Qilian Mountains caused the accumulation of several thousand meters of alluvial fan and fluvial deposits in a north–south trending basin. This basin is filled with large volumes of unconsolidated Quaternary sediments. The sediments from south to north gradually change from coarse-grained gravel to medium and fine-grained sand and silt (Wen et al. 2007). The thickness of deposits ranges from 300–500 m in the south to 100–200 m on the northern edge of the alluvial fan. From south to north, the aquifer transitions from a single-layered shallow aquifer to a multi-layered confined one, and groundwater depth ranged from 200 to 0.5 m in 2013, accordingly. It becomes shallow and gradually transitions to the exposed spring area (Gao and Li 1990), Fig. 2 shows the hydrostratigraphy of the cross-section line (cross-section line of AA′ and BB′ is shown in Fig. 1). From geomorphologic units it can be classified into piedmont alluvial plain, fine soil plain and the Gobi Desert. Groundwater in the Zhangye Basin moves from SE to NW, while in the Eastern Jiuquan Basin, it moves from SW to NE. Modern groundwater is mainly recharged from the limited surface water via river infiltration, canal system seepage and infiltration of irrigation returned flow, and accounts for more than 70 % of the total surface water infiltration into the aquifer under natural conditions (Wen et al. 2008). Springs, river discharge, evaporation from shallow groundwater, and human exploitation are the main groundwater discharge components, of which the annual mean volume of springs and river discharge amount to about 65 % (Hu et al. 2009). Surface water and groundwater exchanges, frequently by vertical infiltration and springs, have formed a typical river–groundwater/spring–river water circulation interaction system (Wen et al. 2007).

Materials and methods

Data sources

Data used in this study are: hydrogeology, terrain, geomorphology, land use and meteorological data, hydrological observation data and irrigation statistical data. The hydrogeology, terrain, geomorphology and meteorological data come from the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) and the Chinese Academy of Science (2015), and include a hydrogeology map (1:500,000), geomorphology map (1:1,000,000), digital elevation model (DEM) (30 m), meteorological data for six weather stations (2000–2010) and land use maps for 1990 and 2010 (1:100,000). The hydrogeology map, geomorphology map, and DEM combined with meteorological data, were used to perform the segmentation of the hydrogeological domain and zones, and land-use maps were used to detect the changes of farmland from 1990 to 2010.

The hydrological observation data obtained from Gansu Provincial Bureau of Hydrology were composed of annual runoff observations from 1980 to 2012 at two Gorge stations on the main canal system, Yingluoxia and Zhengyixia (Fig. 1), and shallow groundwater observations at over 100 monitoring wells. Considering the quality and representativeness of the data, 73 wells with complete continuous records from 1985 to 2013 were selected, which provided groundwater-level and drawdown records on daily, monthly and yearly scales. Most of the wells were mainly focused on the shallow aquifer, and the depth of them varied from 75–240 m in the south to 9–100 m in the north.

The irrigation statistical data collected from the Annual Water Resource Management Reports (1980–2010), and published by the Zhangye Municipal Bureau of Water Conservancy, mainly contained the annual data on water diverted from river, pumped water from subsurface, and consumed water by agriculture and other industry for each irrigation district or county, etc.

Temporal and spatial partition

To better understand the process of how human activities affect water allocation and groundwater system variation, a four-time-stage division from the temporal scale and four partition zones from the spatial scale were generated. During 1980–1989 and 1990–1997, the groundwater system fluctuated with the wet or dry climate to some extent, while with the artificial oasis expansion, especially before and after EWTP (1998–2004, 2005–2013), the effects of climate change were gradually masked by the intensified human activities. So, the four stages were primarily based on the annual average surface runoff volume variations from the entrance of the middle reaches at the Yingluoxia Gauge Station during 1980–2012 in Table 1. If the “Mean runoff volume” is greater (less) than the “Annual average runoff volume” of 16.55×10^8 m^3, it is a wet (dry) year; if it approaches 16.55×10^8 m^3, it is a normal year. During these stages, water diversion and water use contradictions between the middle and lower reaches were prominent, and surface water and groundwater systems underwent great changes.

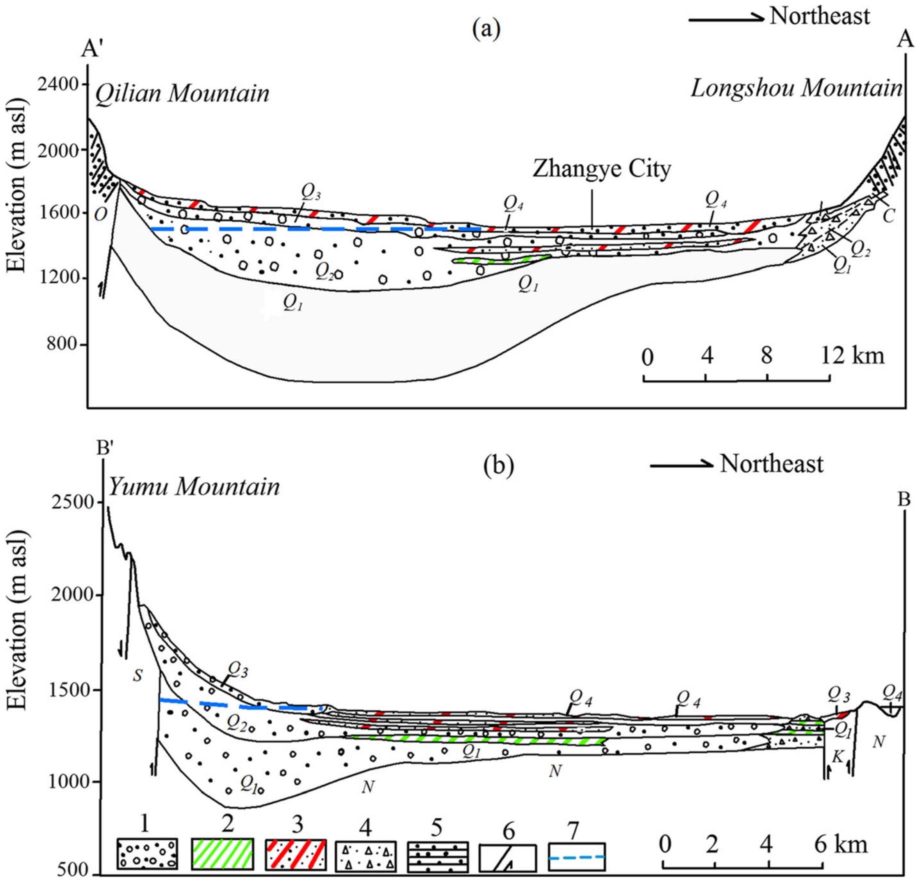


Fig. 2 Hydrostratigraphy along the cross-section line: **a** AA′, **b** BB′. Legend: *1* sand with gravel; *2* clay; *3* sand and silt; 4 sandstone; *5* sandy conglomerate; *6* fault; *7* water table

The hydrogeological boundary was defined by the hydrogeological conditions, and four zones were made accorded to the features of topography, geomorphology, hydrogeology and rainfall characteristics, combined with the structure of the aquifer and groundwater storage conditions: the upper and middle portion of the alluvial fan (I), bottom of the alluvial fan (II), fine soil plain (III) and valley plain (IV) (Fig. 1). The distribution range, natural characteristics, and hydrogeological and irrigated conditions of each zone are shown in Table 2.

Annual groundwater-level drawdown interpolation

The available yearly mean groundwater level data of 73 wells monitored continually from 1985 to 2013 have been used. These wells are distributed across the study area to represent the fluctuation tendency of groundwater level of the whole area of the basin. The data recorded for each well consisted of the average yearly water-table measurements, totaling 2, 117 measurements for all wells in 29 years. Erroneous values, outliers or extreme values are excluded. The annual groundwater-level drawdown (GLD) is the mean groundwater level difference between the base year and the year before for each observation well. For example, the GLD of well Z01 in 1986 is the mean groundwater level difference between 1986 and 1985, and so on. In this calculation, every year could be a base year. Annual GLD of all observation wells during 1985–2013 were calculated. The use of geostatistics for the management and sustainability of water resources of an area have been emphasized by many authors (Kitanidis 1997; Tonkin and Larson 2001; Kumar and Ahmed 2003; Theodossiou and Latinopoulos 2006; Seyed and Abbas 2007), and

Table 1 Conditions of four time stages during 1980–2012

	Stages				
	1980–1989	1990–1997	1998–2004	2005–2012	1980–2012
Annual average runoff volume (10^8 m^3)	–	–	–	–	16.55
Mean runoff volume (10^8 m^3)	17.39	15.08	16.63	18.93	–
Wet or dry conditions	Wet year	Dry year	Normal year	Wet year	–

Table 2 General hydrogeological conditions of subareas and distribution of groundwater observation wells

Zone	Partition	Area (km^2)	Distribution and natural characteristics	Hydrogeological and irrigated conditions
I	Upper and middle part of the alluvial fan	8,666.5	The southern piedmont pluvial-diluvial Gobi plain. Elevation 1,500–2,800 m asl; annual average rainfall 120–300 mm	A single unconfined aquifer. Water table depth >30 m. Dominated by river water. Local well water, or well water and river water mixed in the irrigation district
II	Bottom of the alluvial fan	2,993.6	The connective region of the piedmont pluvial-diluvial Gobi plain and the pluvial fine soil plain. Elevation 1,340–1,830 m asl; annual average rainfall 100–250 mm	From a single unconfined aquifer to a double-confined aquifer. Dominated by shallow water, locally confined groundwater. Water depth 10–30 m. River and well water mixed in the irrigation district
III	Fine soil plain	2,721.9	The central part of the pluvial fine soil plain, which is mainly distributed in Zhangye and Jiuquan. Elevation 1,256–1,680 m asl; annual average rainfall 100–150 mm	Multilayered aquifer structure; main area of confined groundwater and spring water. Water depth <10 m. River and well water mixed in the irrigation district
IV	Valley plain	2,668.1	Alluvial plain distributed along the river valley in Gaotai and Linze counties. Elevation 1,270–1,500 m asl; annual average rainfall 60–130 mm	Multi-layered aquifer structure; confined groundwater area. Water depth <10 m. Well water, spring water and river water mixed in the irrigation district

Kriging is the most popular one. It is an exact interpolation estimator used to find the best linear unbiased estimate (Seyed and Abbas 2007). Kriging is based on the assumption that the parameter being interpolated can be considered a localized variable (Matheron 1963). The semi-variogram $\gamma(h)$, which expresses the spatial dependence between neighboring observations, can be defined as one-half the variance of the difference between the attribute values at all points separated by h as follows:

$$\gamma(h)=\frac{1}{2N(h)}\cdot\sum_{i=1}^{N(h)}\left[Z(x_i)-Z(x_i+h)\right]^2 \tag{1}$$

Where $Z(x)$ indicates the magnitude of variable, and $N(h)$ is the total number of pairs of attributes that are separated by a distance h.

In this study, the Ordinary Kriging on the ArcGIS Geostatistical Analyst Module is applied to analyze the spatial and temporal variations of annual GLD of all wells from 1985 to 2013 in the middle reaches of the HRB. The spherical model and exponential model were used to fit the semi-variation function. It is suggested that QQ-plot normal distribution analysis and trend analysis be conducted before Kriging interpolation to obtain a better interpolation condition. Prediction performances were assessed by cross-validation. Cross-plots of the predicted vs. the measured show the correlation coefficient (R^2). The closer the R^2 to 1, the more appropriate the variogram is. Meanwhile, for a model that provides accurate predictions, the mean error and standardized mean error (SM) should be close to 0, the root mean square error (RMS) and average standard error (AS) should be as small as possible, and the root mean square standardized error (RMSS) should be close to 1 (Johnston et al. 2001).

All of the GLD data for 29 years were assessed by cross validation; some of the validation results are given in Fig. 3 and Table 3. It is shown that the mean error ranged from −0.032 to 0.031, close to 0, and so did the SM error; the RMS ranged from 0.295 to 0.578, as small as an AS error, and the RMSS error ranged from 1.036 to 1.165, which was close to 1. R^2 ranged from 0.49 to 0.58, and for a large-scale region, it is an acceptable prediction performance. Therefore cross-validation shows that the variogram can reasonably represent the spatial structure of the GLD; thus, in this way, the spatial distribution maps of the annual GLD over 29 years were built.

Groundwater storage estimate

The groundwater storage is expressed by the equation as follows (Zhang and Zeng 1994):

$$\Delta W_{ki}=\mu_k\cdot\overline{\sum_{j=1}^{n}\Delta H_{kij}}\cdot F_k \tag{2}$$

In Eq. 2, ΔW_{ki} is the groundwater storage variable for the partition k in year i, k = I, II, III, IV, i from 1985 to 2013, and μ_k is the specific yield of an aquifer for partition k, dimensionless. According to the Gansu Provincial Geological Survey Bureau, the value of μ_k ranges from 0.10–0.15. In this study, partitions I and II were part of the alluvial fan and given values of 0.12; partitions III and IV were part of the alluvial plain and assigned a value of 0.10; ΔH_{kij} is the groundwater level drawdown for grid j in partition k of year i, $\overline{\sum_{j=1}^{n}\Delta H_{kij}}$ is the mean groundwater level drawdown of partition k calculated by the ArcGIS Spatial Analyst module, and F_k is the area of partition k, which is the total area of grid j.

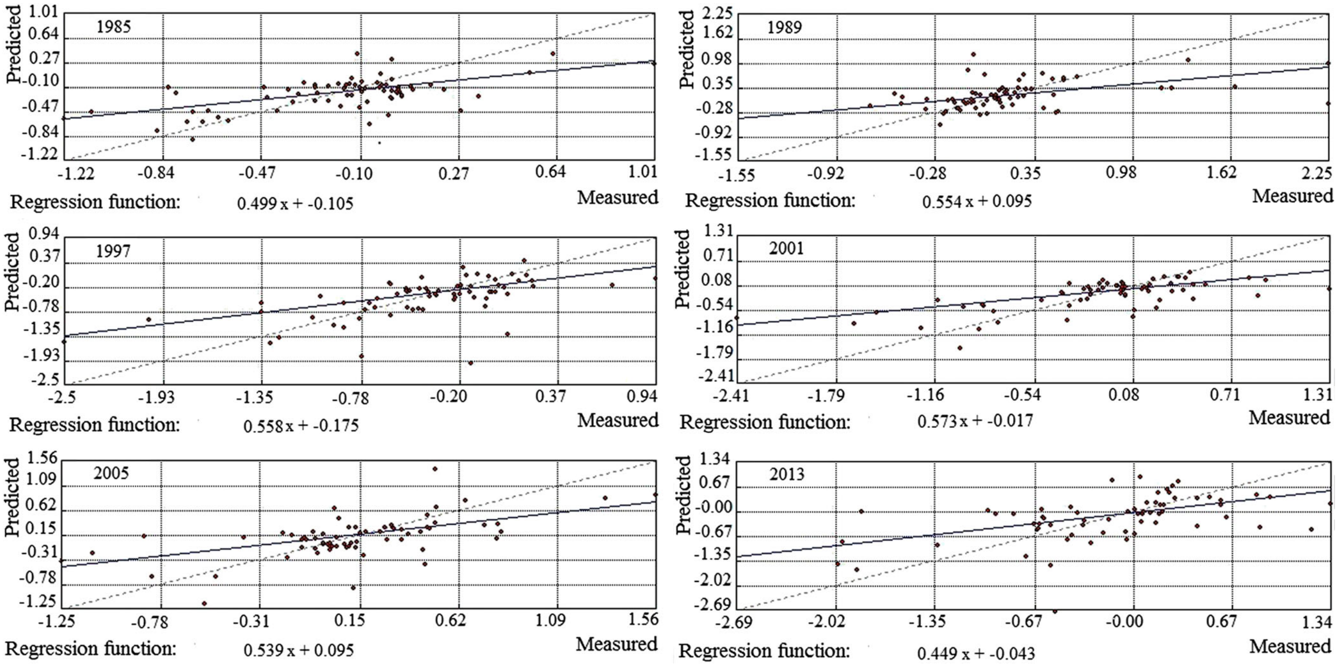


Fig. 3 Cross-validation results of the variograms of the observation wells exported from Kriging interpolation: the *solid line* is the real cross-validation result between measured and predicted, and the *dashed line* is the 1:1 reference line

The annual GLD maps were exported to 730 m × 730 m grid maps separately, and the mean GLD and area was extracted by the four partitions for every year through the ArcGIS Spatial Analyst module. Then groundwater storage of every zone from 1985–2013 was calculated by Eq. 2.

Results

Intensified human activities, especially water diversion and groundwater exploitation for agricultural irrigation, have affected the water resources allocation and re-allocation in the HRB. A series of eco-environmental problems appeared, and not only did the groundwater system fluctuations intensify, but the interactions between surface water and groundwater weakened.

Impact of human activities on the water allocation and its environmental effects

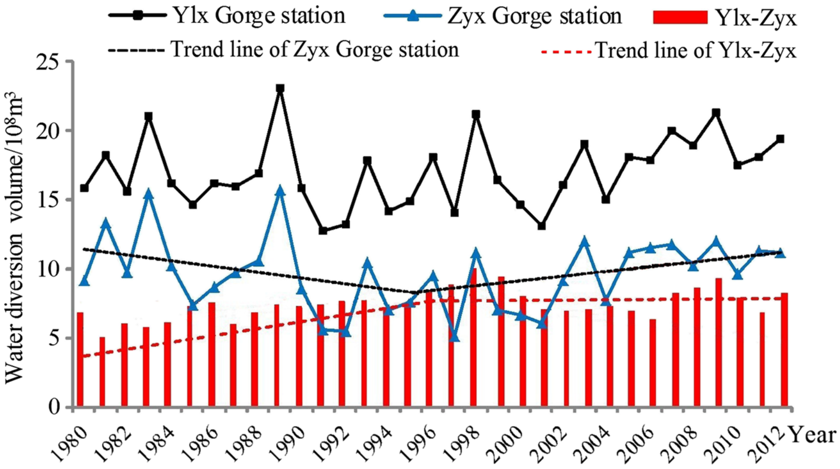
Surface-water allocation between the middle reaches and the lower reaches

In the HRB, the Heihe River is the main surface-water resource used by the middle and lower reaches. As shown in Fig. 4, water measured at Yingluoxia (Ylx) Gorge station represents the total runoff volume of the Heihe River that flows into the middle reaches, while water from Zhengyixia (Zyx) Gorge station is the runoff volume flowing out to the lower reaches, and the difference between Ylx and Zyx (Ylx-Zyx) is the water volume consumed by the middle reaches. Before the EWTP, the water volume of Ylx-Zyx determined the flow volume of Zhengyixia. During 1980–1989 and 1990–1997, with the expansion of cultivated land in the middle reaches, water consumed by agriculture

Table 3 Fitted errors of the theoretical variogram model for GLD

Year	Model	Mean error (mean)	Standardized mean error (SM)	Root mean square error (RMS)	Average standard error (AS)	Root mean square standardized (RMSS)
1985	Spherical	−0.014	−0.038	0.295	0.26	1.064
1989	Spherical	0.031	0.037	0.526	0.436	1.097
1997	Exponential	−0.032	−0.042	0.466	0.377	1.127
2001	Spherical	0.012	0.015	0.547	0.527	1.036
2005	Exponential	0	0.001	0.531	0.516	1.037
2013	Spherical	0.018	0.035	0.578	0.495	1.165

Fig. 4 Surface water diversion to middle and lower reaches in the HRB from 1980–2012



increased, and water volume of Ylx–Zyx increased steadily, while Zhengyixia decreased dramatically and the water allocation ratio between the middle and lower reaches (Ylx-Zyx and Zhengyixia) increased from 0.75 to 1.73. On the one hand, the climate shifted from a wet year to dry year during this period and total water volume from Yingluoxia decreased; on the other hand, water allocation between the middle and lower reaches stayed in a natural state; the middle reaches could always get abundant water to use, and less water flowed to the lower reaches. Water flow was being affected by both climate and human activity during this period. Over the period 1998–2004, the water volume of Ylx-Zyx decreased sharply from 9.98×10^8 m^3 year^{-1} to 7.24×10^8 m^3 year^{-1}, while the amount of water that entered the lower reaches reached 9.9×10^8 m^3 year^{-1} in the year 2000 and increased by 29 %, when compared with the 1990s (Nian et al. 2014), and the water allocation ratio decreased to 0.98. This is the result of the EWPT Project. In order to maintain the ecological water demand and increased cultivated land in the middle reaches, the only way to supplement the scarcity of surface-water resources was to intensify the groundwater abstraction (Table 4). This is one of the main reasons for groundwater system variation. In 2005–2012, runoff volume from Yingluoxia was relatively abundant because of wet years. Both runoff volume in Ylx-Zyx and Zyx increased through artificial adjustment that did not strictly obey the EWPT Project directives. The water allocation ratio between middle and lower reaches reached a dynamic stable level of about 0.7. Water scarcity in the middle reaches was alleviated to some extent. The water resources allocation pattern between the middle and lower reaches shifted from the natural stage to the completely human controlled one.

Water re-allocation and utilization among the middle reaches of the HRB

Water in this region is diverted through canal systems and channels. Channeled irrigation in the middle reaches of the HRB has a history of over 2000 years. There are five main canal systems, named the mainstream of the Heihe River, Liyuan River, Eastern main canal, Western main canal and Mountainous canal, as showed in Fig. 5. Water diverted to the mainstream of the Heihe River, Eastern main canal and Western main canal primarily comes from the Heihe River, to the Liyuan River canal from the Liyuan River, while the water to the Mountainous canal from the Daduma and Hongshui rivers. There are about 6300 irrigation channels now, including the main canal and lateral canal (Hu et al. 2008). These channels are distributed over 21 main irrigation districts that are served by the five main canal systems in the basin. The canal utilization coefficient increased from 60.4 % at the end of 1980s to 65.61 % during 2005–2010 (Table 5).

In addition to canal systems, reservoirs have become an important part of water conservation projects in this region. In all, 42 reservoirs were built by 1989, and the total number of reservoirs reached 46 by the end of the 2000s. As of 2010, the total water storage of the 46 reservoirs was about 8.88×10^8 m^3 year^{-1}. The number of pumping wells has also rapidly increased. Indeed, in the 1980s there were only 2,613 pumping wells, while 6,068 had been installed by 2010 (Table 5). Most of the installed wells were distributed in the Eastern and Western main canal districts and the mainstream of the Heihe River. There were also some in the Mayinghe and Laojun districts of the Mountainous canal (Fig. 5).

As shown in Table 4, it is worth noting that from 1980 to 2004, channeled irrigation water from the five canal systems decreased, and also the total of all channeled irrigation water decreased from 20.06×10^8 to 15.51×10^8 m^3 year^{-1}; however, the total irrigation area in all canal systems presented an increasing trend except for the Mountainous canal system. Daman and Yingke districts in the Eastern main canal system, Xijun and Luotuocheng districts in the Western main canal system, and Mayinghe district in the Mountainous canal system are prominent. The irrigation area in the five districts increased from 1.50×10^4 ha (Daman), 1.89×10^4 ha (Yingke), 1.63×10^4 ha (Xijun), 0.05×10^4 ha (Luotuocheng), and 0.81×10^4 ha

Table 4 Water re-allocation through channels and relevant groundwater abstraction in the middle reaches of the Heihe River Basin during 1980–2010

Irrigation district	1980–1989			1990–1997			1998–2004			2005–2010		
	Channeled irrigation water (10^8 m^3 year^{-1})	Groundwater abstraction (10^8 m^3 year^{-1})	Irrigation area (10^4 ha)	Channeled irrigation water (10^8 m^3 year^{-1})	Groundwater abstraction (10^8 m^3 year^{-1})	Irrigation area (10^4 ha)	Channeled irrigation water (10^8 m^3 year^{-1})	Groundwater abstraction (10^8 m^3 year^{-1})	Irrigation area (10^4 ha)	Channeled irrigation water (10^8 m^3 year^{-1})	Groundwater abstraction (10^8 m^3 year^{-1})	Irrigation area (10^4 ha)
Liyuan River Canal System												
Liyuan River (only)	1.34	0.33	0.78	1.44	0.26	1.61	1.30	0.06	2.05	1.47	0.16	2.12
Main Heihe River Canal System												
Yanuan	0.46	–	0.31	0.49	0.00	0.36	0.49	0.04	0.36	0.48	0.08	0.36
Liaoquan	0.65	–	0.37	0.60	0.00	0.45	0.52	0.08	0.46	0.47	0.08	0.46
Banqiao	0.75	–	0.33	0.86	–	0.54	1.07	0.04	0.60	0.81	0.03	0.60
Pingchuan	0.98	–	0.53	0.79	0.01	0.61	0.60	0.19	0.62	0.58	0.18	0.62
Sanqing	0.48	–	0.31	0.49	0.33	0.41	0.45	0.25	0.42	0.45	0.05	0.42
Youlian	0.94	–	0.55	0.99	0.07	0.84	0.69	0.21	1.03	0.91	0.30	1.04
Dahuwan	0.64	–	0.34	0.32	0.01	0.31	0.28	0.02	0.31	0.28	0.07	0.31
Liuba	0.37	–	0.20	0.19	0.05	0.22	0.22	0.18	0.36	0.17	0.08	0.36
Luocheng	0.33	–	0.22	0.13	0.01	0.22	0.25	0.13	0.46	0.27	0.15	0.46
Total	5.61	–	3.15	4.86	0.49	3.97	4.58	1.14	4.62	4.41	1.01	4.64
Eastern Main Canal System												
Daman	1.95[a]	0.03[a]	1.50[a]	1.69[a]	0.13[a]	1.50[a]	1.34[a]	0.88[a]	2.27[a]	1.36[a]	1.19[a]	2.41[a]
Yingke	3.13[a]	0.10[a]	1.89[a]	2.47[a]	0.41[a]	1.89[a]	1.54[a]	0.88[a]	2.11[a]	1.73[a]	0.70[a]	2.11[a]
Shangsan	0.88	–	0.47	0.78	–	0.48	0.89	–	0.68	0.96	0.01	0.68
Total	5.96	0.13	3.86	4.94	0.54	3.87	3.77	1.76	5.06	4.05	1.90	5.19
Western Main Canal System												
Xijun	2.99[a]	0.01[a]	1.63[a]	2.35[a]	0.11[a]	1.83[a]	1.71[a]	0.69[a]	1.90[a]	1.78[a]	0.60[a]	1.90[a]
Shahe	0.40	0.01	0.26	0.43	0.05	0.50	0.24	0.15	0.50	0.30	0.23	0.50
Luotuocheng	–	0.04[a]	0.05[a]	0.01[a]	0.39[a]	0.36[a]	0.05[a]	0.54[a]	0.49[a]	0.08[a]	0.50[a]	0.49[a]
Total	3.39	0.06	1.94	2.79	0.54	2.69	2.00	1.38	2.88	2.16	1.33	2.88
Mountainous Canal System												
Daduma	1.04	–	2.46	0.86	–	1.12	1.37	–	1.85	1.41	–	1.93
Hongshuihe	1.39	–	3.46	1.08	–	1.82	1.12	–	1.87	1.18	–	2.04
Tongziba	0.68	–	1.50	0.50	–	1.05	0.68	–	1.07	0.60	–	1.28
Mayinghe	0.65[a]	0.03[a]	0.81[a]	0.78[a]	0.33[a]	1.21[a]	0.61[a]	0.40[a]	1.84[a]	0.75[a]	0.51[a]	1.81[a]
Laojun	–	–	0.07	0.04	0.01	0.11	0.07	0.00	0.14	0.04	0.00	0.44
Total	3.76	0.03	8.31	3.25	0.34	5.30	3.86	0.41	6.77	3.99	0.51	7.51
Total for all canal systems	20.06	0.55	18.03	17.27	2.18	17.44	15.51	4.73	21.39	16.09	4.92	22.34

[a] Refers to irrigation districts analysed in the context with all the items undergoing obvious changes

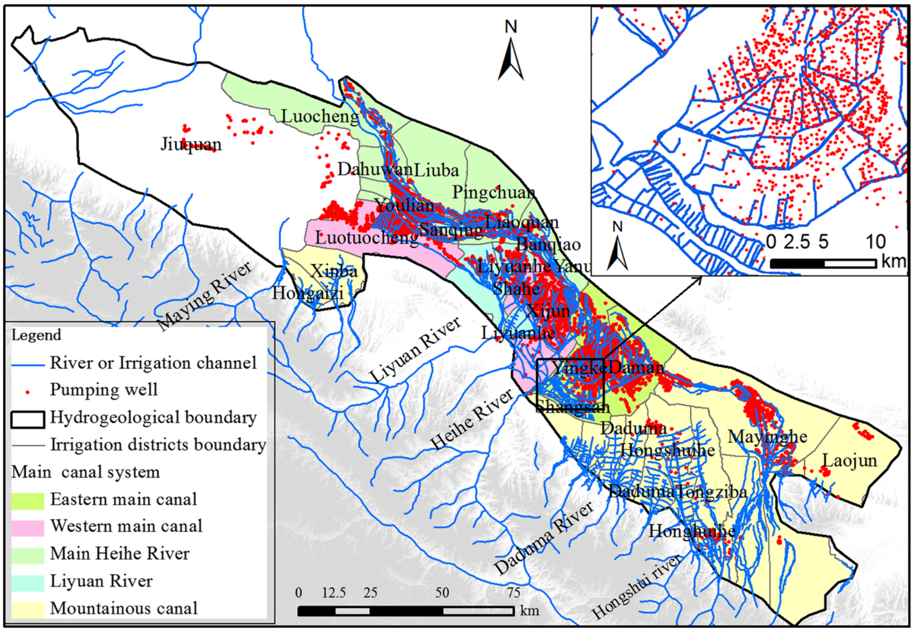


Fig. 5 Main irrigation canal systems, canal districts and groundwater exploitation wells in the study area. The *dark box* (inset map) shows the Eastern main canal system. Canals, channels and wells are orderly distributed over the Yingke and Daman district

(Mayinghe) in 1980–1989 to 2.27×10^4, 2.11×10^4, 1.90×10^4, 0.49×10^4, and 1.84×10^4 ha during 1998–2004, respectively. Because more irrigation water was needed, coupled with the unbalanced distribution of water over these irrigation districts, the amount of groundwater abstraction increased dramatically from 0.03×10^8, 0.1×10^8, 0.01×10^8, 0.04×10^8 and 0.03×10^8 m^3 year^{-1} in 1980–1989 to nearly 0.88×10^8, 0.88×10^8, 0.69×10^8, 0.54×10^8 and 0.40×10^8 m^3 year^{-1}, in 1998–2004, respectively; In 2005–2010, the total volume of all channeled irrigation water increased to 16.09×10^8 m^3 year^{-1}. At the same time, the increased growth rate of irrigation area slowed down, some irrigation area remaining almost unchanged except for the Daman irrigation district and the irrigation districts of the Mountainous canal, such that the intensity of groundwater abstraction lowered accordingly. This might be associated with the establishment of the water-saving society and agricultural structure adjustment after the EWTP.

Evolution of the groundwater system

As previously mentioned, continuous expansion of cropland combined with unbalanced water allocation and re-allocation contributed considerably to the vast groundwater abstraction from the deep aquifer. This accelerated lowering of the water table and groundwater storage, so spatial and temporal variability of the groundwater system were deeply affected.

Water-table fluctuations

From the viewpoint of different partitions, as showed in Table 6, groundwater levels in zones I and II showed a regional decline during 1985–2013; the maximum cumulative groundwater level dropped 17.41 and 11.49 m, and maximum annual average decline rate reached 0.60 and 0.40 m year^{-1} respectively. Relatively smaller cumulative declines were recorded in zones III and IV, and the maximum annual average decline rate reached 0.27 and 0.17 m year^{-1}, respectively.

From different time stages (Table 6), groundwater level in every partition exhibited a decline tendency during 1985–1997. The maximum annual average decline rate reached 0.46 and 0.36 m year^{-1} in zones I and II. Because of the weather pattern shift from wet year to dry year, the amount of water from the Heihe River reduced, and recharge by river leakage to the underground in zones I and II decreased too.

Table 5 Water resources development in the middle reaches of the HRB since 1980

	Years			
	1980–1989	1990–1997	1998–2004	2005–2010
No. of reservoirs	42	44	43	46
Reservoir storage (10^8 m^3)	6.28	6.45	7.76	8.88
Canal utilization coefficient (%)	60.40	67.29	63.62	65.61
No. of pumping wells	2613	4724	5484	6068
Groundwater abstraction (10^8 m^3)	0.55	2.18	4.75	4.97

Table 6 Groundwater level fluctuation for all observation wells

Zone	Annual mean variation of groundwater level in four stages (m year^{-1})				Total variation in groundwater level (ΔH/m)	Annual mean variation in groundwater level (m year^{-1})
	1985–1989 (wet year)	1990–1997 (dry year)	1998–2004 (normal year)	2005–2013 (wet year)		
I	−0.33–0.07	−0.46–0.01	−0.98 to −0.38	−0.54–0.26	−17.41 to −0.43	−0.60 to −0.01
II	−0.24–0.13	−0.36 to −0.11	−0.83–0.14	0.15–0.37	−11.49 to −0.29	−0.40 to −0.01
III	−0.1–0.12	−0.15–0.06	−0.34–0.07	−0.16–0.22	−7.78–2.25	−0.27–0.08
IV	−0.1–0.06	−0.23–0.02	−0.44–0.07	−0.19–0.13	−4.92–1.06	−0.17–0.04

From 1998 to 2004, the annual average groundwater level decline rate accelerated obviously in each zone, though it was a normal year. The maximum annual average decline rate reached 0.98 and 0.83 m year^{-1} in zones I and II respectively but a relatively slow decline rate of 0.34 and 0.44 m year^{-1} was recorded in zones III and IV. Groundwater level drawdown was directly correlated with the expanded irrigation area and groundwater exploitation. Meanwhile, the groundwater level of individual observation wells appeared to rise a little after 2001. During 2005–2013, with a number of long wet years experienced, more river-leakage recharge was achieved and the groundwater abstraction alleviated. Groundwater level decline rates slowed down in every zone. The maximum decline rate decreased to 0.54 m year^{-1} in zone I, with a rising tendency appearing in zone II, and a steady state and a little rising in zones III and IV.

Groundwater levels in three observation wells (Z13, Z22, Z121) in Daman and two wells (G01, G08) in Luotuocheng irrigation districts, which are located in zones I and II, declined obviously from 1985 to 2013, as showed in Fig. 6. These districts were mixed-river-and-well or well-water irrigated; canal seepage and irrigation returned flow infiltration were the main recharge, and groundwater abstraction was the main discharge. The water table was primarily controlled by the irrigation area and groundwater abstraction. Because of water re-allocation in these two irrigation districts, the amount of surface water was reduced, and the increased cultivated land area induced a large amount of groundwater abstraction. Meanwhile, because these districts are far from the main Heihe River, there was almost no recharge from river leakage, so there was widespread water table decrease from 11.49 to 17.41 m depth.

It was noted that after 2001, a wide range of rising groundwater levels appeared continuously over the Eastern Jiuquan basin and Main Heihe River; the cumulative increase of the groundwater level reached 0.1 ~ 3.3 m, and the increase of the amplitude in zones I and II was greater than in zones III and IV (Fig. 6). Observation wells distributed in Yingke (Z04, Z06), Xijun (Z33) and Banqiao (L13, L17) irrigation districts were rather typical. These regions were mainly river-, spring- and well-water mixed irrigation areas, and the maximum proportion of surface-water irrigation was more than 80 %. River leakage, canal seepage and irrigation return flow infiltration were the main recharge; evapotranspiration, spring flow and groundwater abstraction were the main discharge. The water table was primarily controlled by the river leakage and groundwater abstraction. In contrast to the year 2000, there was almost no increase of cultivated land in these districts, so there was a slight decrease in groundwater abstraction; for example, groundwater exploitation in Yingke irrigation district decreased by 0.18×10^8 m^3. It was shown that the main reasons for the groundwater level rising were the increased river leakage and decreased groundwater exploitation. Hu et al. (2012) found that river leakage in the middle and upper reaches of the main Heihe River increased by 3.12×10^8 m^3 after water diversion. Although a wide range of increase appeared in the records after 2001–2004, in the long run, the accumulative groundwater level still tended to decrease.

Groundwater storage variations

The groundwater storage variations reflected long-term water table variations and groundwater balance, which were estimated based on temporal and spatial fluctuations of groundwater level. Data as shown from Fig. 7 and Table 7 illustrate that during 1985–2013, the groundwater cumulative storage decreased by 177.52×10^8 m^3, of which groundwater storage in zone I decreased by 168.18×10^8 m^3. This accounted for about 94.7 % of the cumulative decrease, and exhibited a severely negative balance. The cumulative storage decrease in the other three zones was about 9.33×10^8 m^3.

In zone I, the annual average reduction rate of groundwater storage increased from 1.46×10^8 m^3 year^{-1} in 1985–1989 to 6.88×10^8 m^3 year^{-1} in 1998–2004, reaching a maximum of 14.00×10^8 m^3 year^{-1} in 1998–2004. After 2004, a slowing down of the reduction rate of 0.87×10^8 m^3 year^{-1} occurred. In the other three zones, the annual average reduction rate was small, indicating a relatively dynamic balance between recharge and discharge during the four time stages.

Discussion

The characteristics of water resources and the way they are allocated in the middle reaches of the HRB determined the

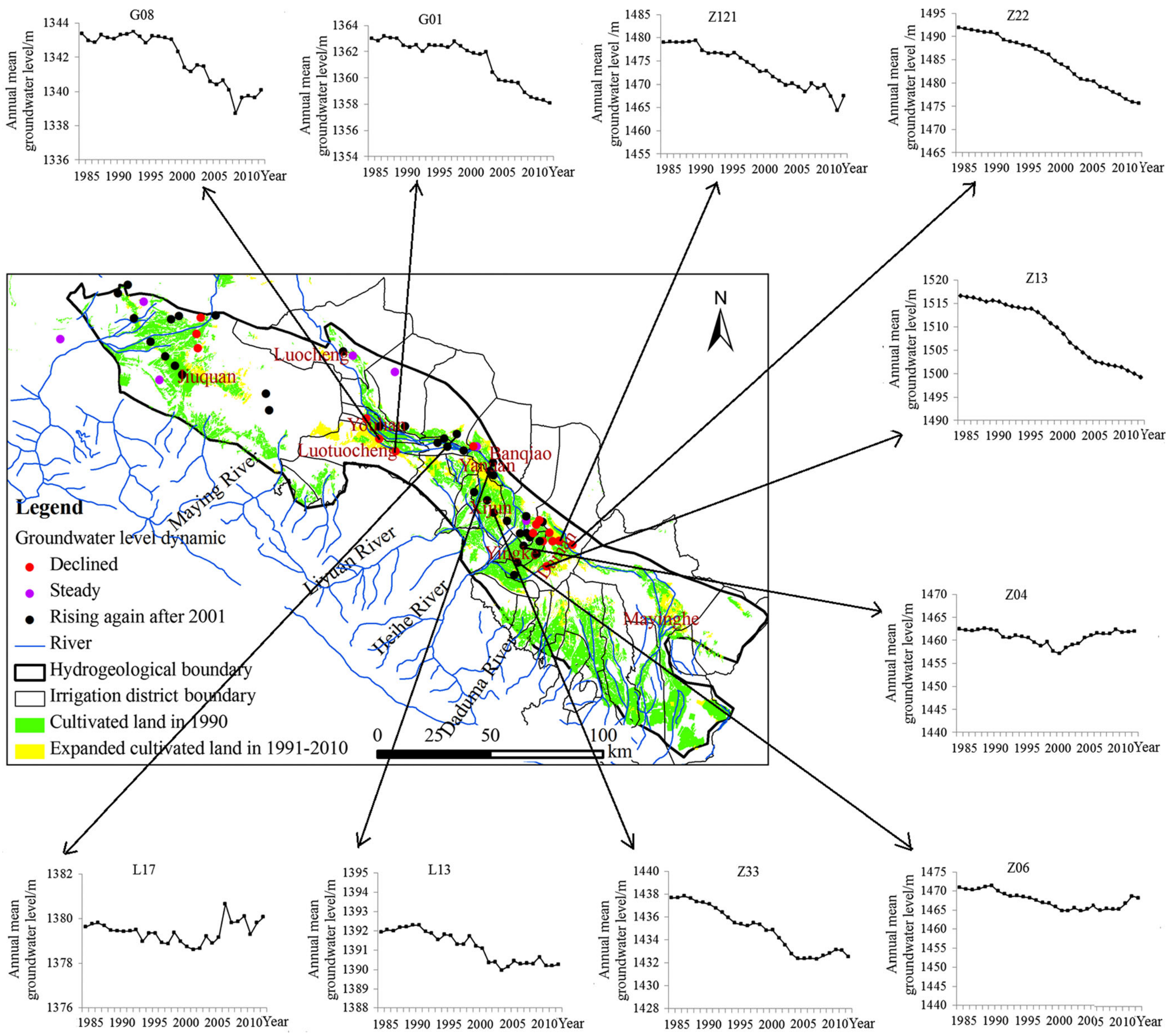


Fig. 6 Annual average groundwater level in the middle reaches of the HRB from 1985 to 2013. *Red* points indicate observation wells with decreasing water table throughout the study period, and *black* points indicate the rising trend after 2001

temporal and spatial variations of groundwater resources, which brought a new challenge to water resources management over the whole river basin. Water-resource-allocation imbalance is one of the main reasons for excessive exploitation of groundwater resources in the middle reaches. On one side, irrational water resources allocation between the middle and lower reaches remained unresolved. Before the EWTP (in 2001), water allocation was in a relatively natural state, no matter whether in wet or dry years; the middle reaches were always given the priority for receiving water resources, and water resources were relatively abundant. After the EWTP was initiated, the lower reaches received a greater water allocation while the middle reaches were given lower priority and received less of the water resources. On the other side, unbalanced water resource allocation over canals and irrigation districts still existed. The continuous expansion of cultivated land with different expansion rates in different irrigation districts meant that agricultural water use also increased with different rates in different irrigation districts; larger differences were caused by the allocation of water resources among the canal systems and at the same time this caused the establishment of a large number of mining groundwater pumps to compensate for the relative shortage of surface water resources in the middle reaches.

As a result, the water table and groundwater storage showed large temporal and spatial differences over the most recent 30 years. Over the whole of the middle reaches, water tables and storage experienced a process of steady decline in

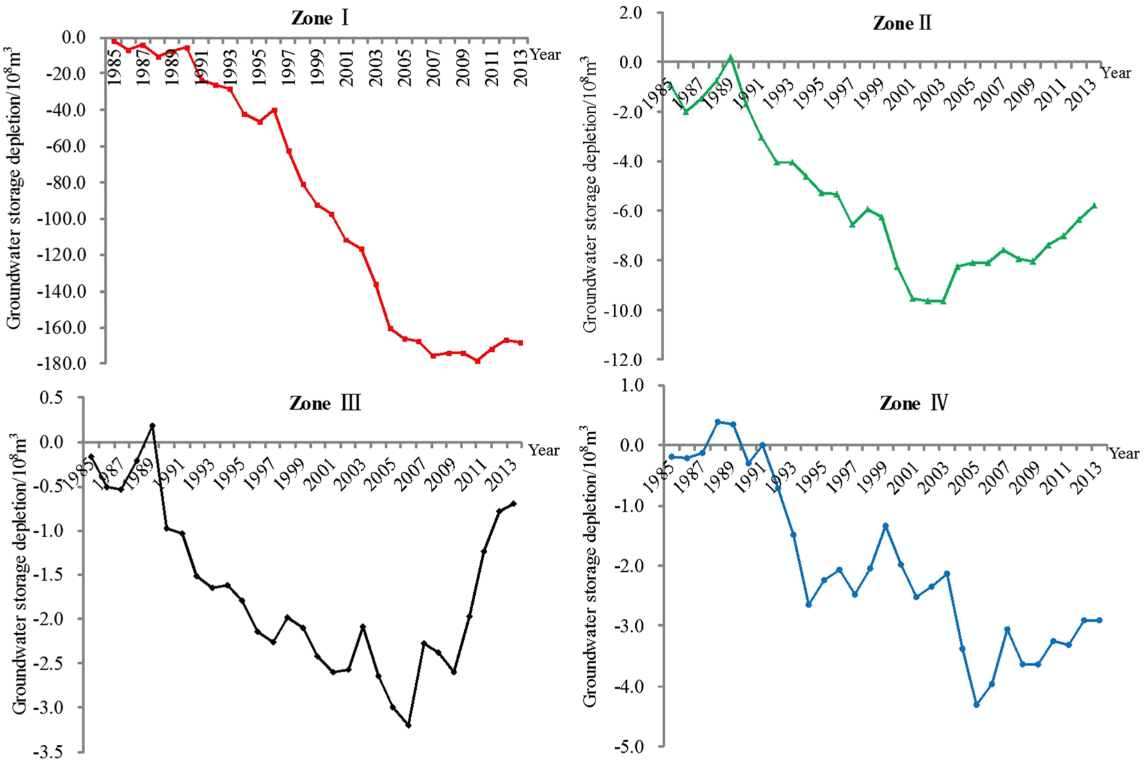


Fig. 7 Variations of cumulative groundwater storage in the four zones from 1985 to 2013

the period of 1985–1997, a rapid decline in 1998–2004, to a relative slowing down of depletion in 2005–2013. During 1985–1997, the water table fluctuated with the wet and dry years to some extent, and at this time the effects of human activities were not very prominent; from 1998 to 2013, with the intensified human activities, the ability to control and allocate the water resources becomes a more and more powerful influence. The processes, from the expansion of cultivated land, the increasing groundwater exploitation and unlimited water diversion to the limiting of cultivated land expansion and groundwater exploitation, and the limiting of surface-water diversion, were directly reflected by the water table and storage changes. Especially noted was the implementation of the EWTP reinforcing the impact of human activities, groundwater system variations and groundwater/surface-water interactions, and even the hydrological process was fundamentally disturbed by human activities. As shown in Figs. 8 and 9, it was found, surprisingly, that the trend of groundwater depletion was very similar to the groundwater abstraction rates in the middle reaches of the HRB, and the mean water-table elevation fluctuations were closely related to the volume of groundwater abstraction; R^2 almost reached 0.99. From the aspect of partitions, different zones showed different water-table decline rates, as did storage. It was noteworthy that during these different time stages, a maximum water-table decline rate and storage reduction was met in zone I, which was in line with the predecessors' research results (Yang and Wang 2005; Wei et al. 2008; Hu et al. 2009). This may be primarily associated with the hydrogeological environment, groundwater recharge and discharge condition. Zone I is a single-layered unconfined aquifer with a large thickness and deep groundwater depth. It lies in the groundwater runoff belt; the hydraulic gradient was high and the groundwater flow rate and renewable rate were fast.

Table 7 Groundwater storage variations in four zones from 1985 to 2013

Zone	Cell count	Area (km^2)	Annual average variation in groundwater storage (10^8 m^3 year^{-1})				Cumulative variation (10^8 m^3)
			1985–1989	1990–1997	1998–2004	2005–2013	
I	17,669	8,657.81	−1.46	−6.88	−14.00	−0.87	−168.18
II	6,121	2,999.29	0.05	−0.84	−0.25	0.28	−5.75
III	5,553	2,720.97	0.04	−0.31	−0.05	0.22	−0.70
IV	5,445	2,668.05	0.07	−0.35	−0.13	0.05	−2.90
Total	34,788	17,050.12	−1.41	−9.31	−13.08	−0.32	−177.52

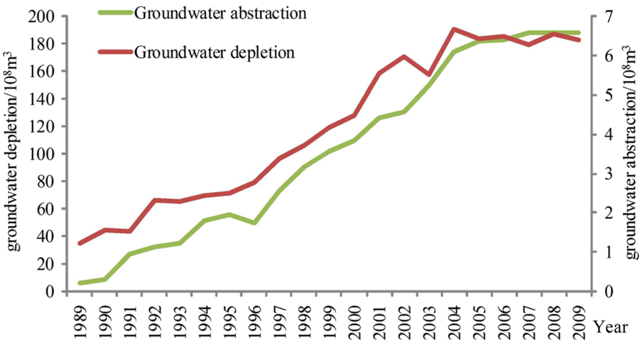


Fig. 8 Trend of groundwater depletion and groundwater abstraction

Table 8 Recharge and discharge in the middle reaches of the HRB during the 20th century

	Years					
	1950s	1960s	1970s	1980s	1990s	1999
Total recharge (10^8 m^3 year^{-1})	31.06	27.93	23.86	22.29	21.55	20.75
Canal infiltration (10^8 m^3 year^{-1})	15.07	13.08	11.41	10.32	7.87	12.94
Spring discharge (10^8 m^3 year^{-1})	12.72	10.66	10.52	10.99	7.74	7.00

Groundwater recharge was mainly river and canal seepage. With the improvement of the utilization rate of canal water, groundwater recharge has decreased during the last 30 years. There were mainly river water and mixed-river-and-well water irrigation districts in this region, and a high level of groundwater abstraction for a long time with no supplement; groundwater storage transformed to groundwater runoff and, therefore, the water table and storage were bound to decline.

After the EWTP was established, cultivated land expansion was under control and groundwater exploitation intensity slowed down. The water table and storage decline rate slowed down and actually showed a little rise again in some areas, especially near the river. The nearer the river, and the more water infiltration recharge, the more significant was the groundwater level rise. However, regions in the alluvial fan (zone I) far away from the river received no river or other recharge, the water table (storage) still tended to decline. Control of cultivated-land expansion and groundwater exploitation had had a positive impact on the groundwater system of the middle reaches.

From the aspect of hydrological processes and mechanisms of recharge and discharge, water diversion, groundwater exploitation and other human activities had changed the land use, cover condition and patterns of traditional water resources utilization which had a certain hydrological effect on the groundwater system. With the function of groundwater recharge and discharge changing to a certain extent, surface-water/groundwater interaction was influenced over the whole basin. The total recharge of the middle reaches decreased from 31.06×10^8 m^3 year^{-1} in the 1950s to 20.75×10^8 m^3 year^{-1} in 1999. This was accompanied by a corresponding decrease of canal infiltration from 15.07×10^8 to 12.94×10^8 m^3 year^{-1}. Spring discharge also decreased from 12.72×10^8 m^3 year^{-1} in the 1950s to 7.00×10^8 m^3 year^{-1} in 1999 (Table 8). Before and after the establishment of the EWTP, the annual average irrigation returned water infiltration decreased from 1.91×10^8 to 1.72×10^8 m^3 year^{-1}, while the mean spring discharge decreased from 7.00×10^8 to 4.87×10^8 m^3 year^{-1}.

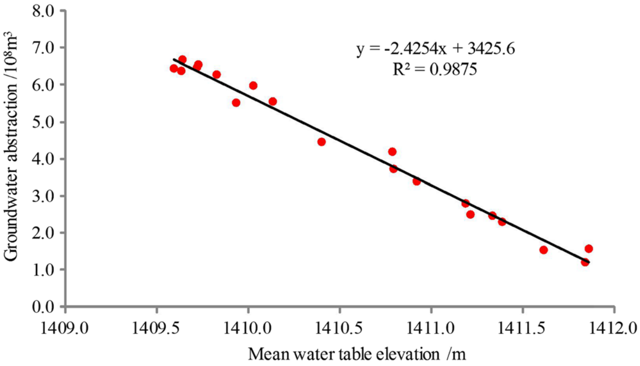


Fig. 9 Groundwater abstraction and mean water-table elevation in the middle reaches of the HRB

Due to the limited data, a possible uncertainty of the estimation on the groundwater storage levels may exist in regions with little or no data, such as the Maying basin in the east of the basin. It is inevitable in such a large-scaled region, that the estimated general trend of variations is consistent with the predecessors' research results. In future work, a basin-scaled groundwater model can be established based on the complete understanding of groundwater system variations, to validate the estimation results with each other.

Conclusions

Irrational allocation, development and utilization of water resources may harm the sustainability of groundwater systems. The interaction functions of surface water and groundwater will be lost and ultimately lead to degradation of the overall water environment. The results of this study indicate that groundwater-level and storage decline rates have slowed down in the last few decades; however, the groundwater system is still suffering from a serious threat, especially in the alluvial fan. The temporal and spatial variation of the groundwater system in the middle reaches was the result of increasing impact from human activities.

The water resource issues in the HRB are common in the inland river basins in China such as Tarim River Basin and Shiyang River Basin. The implementation of the water diversion project to a certain extent relieved the contradictions of water use between the middle and lower reaches; meanwhile new problems arose. The present water diversion policy in the short term can solve the problem of water resources allocation between the middle and lower reaches, but in the long run, problems of how to configure water resources to better reflect the sustainable development of water resources remained unresolved. The urgent issues are to adjust the water diversion policy and to optimize the proportion (curve) of water diverted to the middle and lower reaches according to the dry or wet years. Water transfer quantity and transfer times should also be further optimized, and there should be joint surface-water and groundwater management to realize optimal operation.

To better cope with the groundwater problems in middle reaches of HRB, three countermeasures can be implemented. Specifically, a rational "ecological water diversion plan" can be developed to reallocate surface water and groundwater between various water users and the middle and lower parts of the basin. Second, "critical zones" can be constructed on irrigation-district scale in the middle reaches of the HRB, especially in the Zhangye Basin. Wet land can be constructed in the "critical zones" in the irrigation districts of groundwater level decrease, and in the "critical zones" in the irrigation districts of groundwater level increase, taking proper abstraction to balance the water table. Finally, some wells should be shut down, the irrigation area should be controlled, and further over-exploitation should be regulated. A comprehensive observation network should be established to monitor the dynamics of water resource utilization and the change in surface-water/groundwater interaction.

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