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Long-term groundwater dynamics affected by intense agricultural activities in oasis areas of arid inland river basins, Northwest China

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ABSTRACT

Oasis areas of arid inland river basins in northwest China have been facing intensified water use conflicts between agricultural sector and eco-environmental systems since 1990s. The reduction of river water allocation to oasis has resulted in the undesirable declines of groundwater levels (GWLs) with the increase in irrigated area and groundwater pumping. Improving water management and restoring GWLs become a great concern for those areas. In this study, the middle oasis of Heihe River basin (HRB) was selected as the representative case for such an endeavor. A three-dimensional groundwater flow model was established for the Zhangye basin, a sub-basin of HRB to obtain a better understanding of groundwater dynamics in middle oasis, particularly for investigating the effects of agricultural water use. A major advantage of this model is that the spatial and temporal recharge from irrigation has been described in details with considering the result obtained by an ago-hydrological model (SWAP-EPIC) simulation. The model was well calibrated and validated over the period of 1991–2010. Simulation of GWLs matched well with the observed 20-year GWLs in the 50 wells. Then, spatiotemporal groundwater dynamics and groundwater budget were quantitatively analyzed for the Zhangye basin during 1991–2010. In particular, the modeling results revealed three different changing trends of GWLs based on the analysis of groundwater dynamics and budget for four representative zones. Results indicated that negative balance of groundwater was mainly caused by over exploitation of groundwater for irrigation, resulting in a GWL decline of 9 cm a^{-1} in average and even 2 m decline in some years at local areas. The area with critical groundwater depth (e.g. < 5 m) has reduced about 30% in 2010 as compared to that in 1991. Finally, recommendations on how to restore GWLs were proposed with emphasis on irrigation water and land use adjustment and groundwater pumping control. Our results are expected to provide implications for recovering the groundwater status in oasis areas of inland river basins in arid northwest China.

1. Introduction

Water scarcity and resulting water use conflicts have become a great concern to river basin management in arid and semi-arid areas worldwide. The challenge is more serious to most arid inland river basins with large irrigated agriculture (Ji et al., 2006; White et al., 2014; Cheng et al., 2014). In arid northwest China, the rapid expansion of irrigated agriculture has further aggravated the water use conflicts between agriculture and eco-environment in the basin in recent decades. The conflicts are especially striking for most inland river basins, i.e. Tarim River basin, Heihe River basin, Shiyanghe River basin and Shule River basin (Fig. 1), especially since 1990s (Cheng et al., 2006; Zhang et al., 2014). The Ecological Water Diversion Project (EWDP) has been implemented in these basins with the purpose of decreasing river water allocation to artificial oasis and aiming to restore ecosystems in downstream basin since 2000 (Cheng et al., 2014). However, application of EWDP has resulted in over-exploitation of groundwater for irrigation supplement, and thus continuous decline of groundwater levels (GWLs) and ecosystem deterioration in the oasis (Cheng et al., 2014; Kang et al., 2008; Huang and Pang, 2010; Zhang et al., 2014). Therefore, a thorough understanding of long-term groundwater dynamics affected by agricultural water use is quite necessary and should be the basis for restoring groundwater environment in oasis areas.

Various researches have been carried out to investigate the hydrological processes for seeking reasonable groundwater management in oasis areas. The studies involve different aspects of processes and various techniques related to groundwater system, e.g. traditional field experiments (Jiang et al., 2015; Chen et al., 2006), geostatistical

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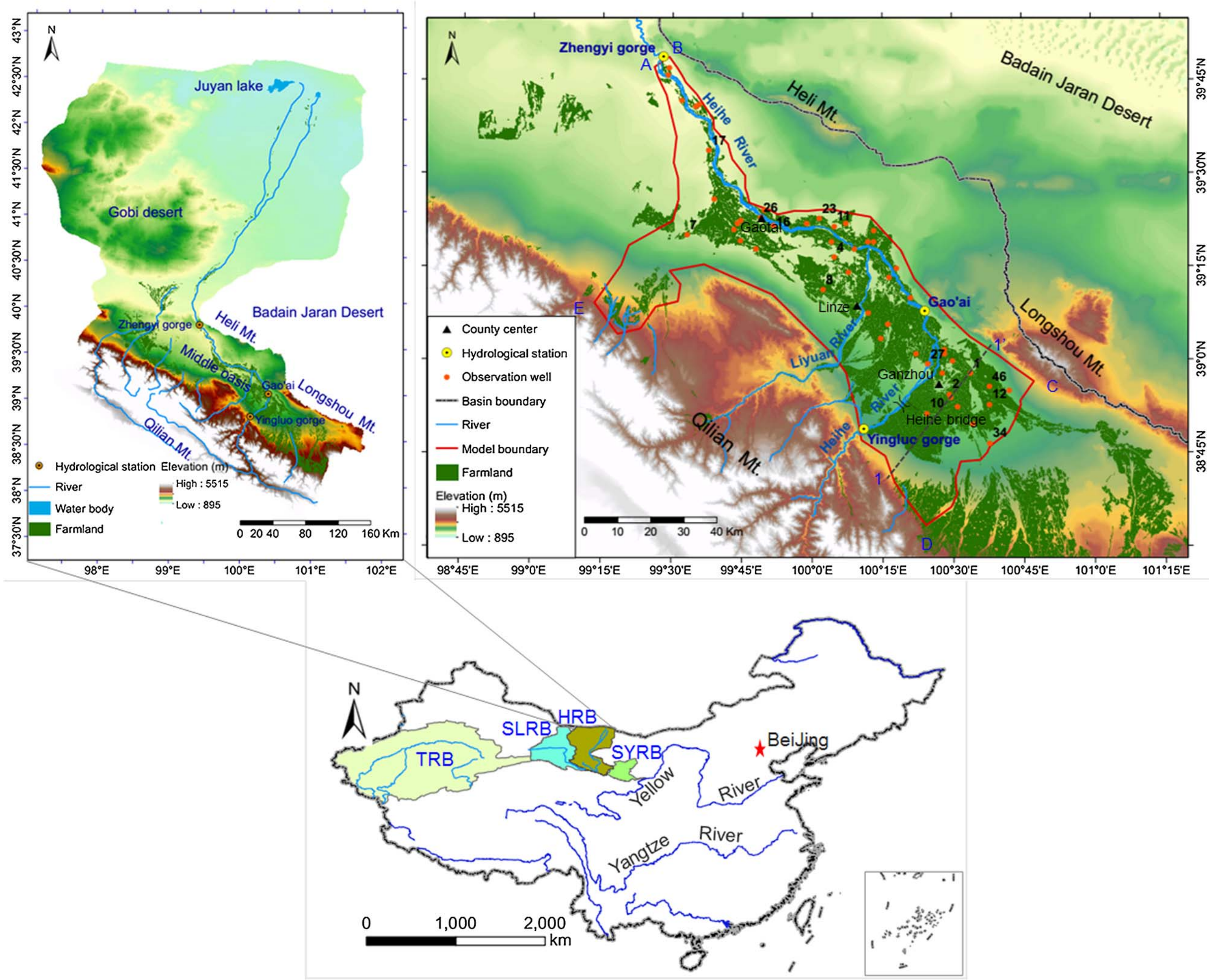

Fig. 1. Location and hydro-geological conditions of the modeling area (Zhangye basin) in the middle Heihe River basin, and distribution of farmlands and groundwater observation wells (the middle reach are defined as the reach between Yingluo gorge and Zhengyi gorge).

analysis (Hu et al., 2012), remote sensing inversion (Zhao et al., 2013), simulation modeling (Li and Zhao, 2010; Peng and Xu, 2010), water chemistry (Huang and Pang, 2010) and tracer (temperature or isotope) experiments (Huang and Pang, 2010; Yao et al., 2015a; Zhu et al., 2008). Recently, the regional-scale hydrological modeling is increasingly considered as a promising tool accomplishing the research objectives (Cheng et al., 2014). In particular, the models with groundwater flow model as the core are preferred and widely adopted in former literatures, because of the important role of groundwater and its frequent interactions with surface water in oasis areas (Zhou et al., 2011; Wu et al., 2014; Li et al., 2017; Huo et al., 2011; Danierhan et al., 2013; Xie et al., 2012). In such way, all the key aspects of hydrological cycles and their interactions could be combined and integrated in the modeling. However, in most previous studies in arid inland river basins of northwest China, the effects of agricultural irrigation on hydrological cycle are significant but usually treated with very simple and not necessarily physically-sound approaches. For instance, irrigation recharge (including canal seepage, field deep percolation) is often simplified as an empirical ratio to irrigation or even uniform distribution in an irrigation system (e.g. Wen et al., 2007; Huo et al., 2011; Zhou et al., 2011; Yao et al., 2015b). Nevertheless, note that they often have very strong spatial and temporal variations in oasis, affected by water conveyance and field irrigation conditions, irrigation management, crop patterns, soils, etc. (Jiang et al., 2015; Jiang et al., 2016; Jiang, 2017). The over-simplified approaches are partly caused by the limitation of data availability, and partly due to the poor understanding of the agro-hydrological processes. On the other hand, the groundwater dynamic analysis in most previous studies are carried out with a relatively short calibration period (mainly 2–6 years) (e.g. Huo et al., 2011; Hu et al., 2007; Xie et al., 2012; Wu et al., 2014). This may not well reflect the long-term dynamics of groundwater dynamics in oasis area. Therefore, this study is to investigate the long-term effect of intense agricultural activities on groundwater dynamics in recent decades with the middle oasis of the Heihe River basin as a typical example, mainly taking into account the huge amounts of shared data in hydrology, hydrogeology, agriculture, land use pattern etc.

The Heihe River basin (HRB) is the second largest inland river basin in China, covering an area of 128,000 km^2. It consists of an upstream mountain area, a piedmont plain and fine-soil valley plain in midstream area (i.e. middle oasis), and a downstream area of Gobi desert and wetlands (Fig. 1). In recent years, excessive diversion for agriculture in the middle oasis has resulted in inadequate discharge to the downstream areas. This has raised a few significant ecological issues especially since 1990s, typically as natural vegetation degradation, soil desertification and terminal lake shrinkage (Guo et al., 2009; Cheng et al., 2014). With the application of EWDP, the positive effects are observed in downstream area at least in the short-term, e.g. the recovery of Juyan Lake and wetlands (Zhu et al., 2013, Wang et al., 2014). In another aspect, more groundwater is exploited for irrigation and significant GWL decline is observed in many parts of middle oasis since 1980s, as reported in some previous studies (e.g. Zhou et al., 2011; Mi et al., 2015; Jiang, 2017). The shrinkage of wetland and degradation of natural vegetation has occurred in some local regions. Thus, it is essential to quantitatively recognize the effects of agricultural activities on water cycle and groundwater dynamics. At present, how to prevent the water table decline and recover the groundwater environment is becoming an urgent issue for the middle oasis.

Taking into account the above mentioned issues, this paper aims at exploring the long-term groundwater dynamics in middle oasis in recent two decades with detailed consideration of irrigation effects, on the basis of previous groundwater modeling and agro-hydrological modeling. The large volume datasets, particularly related to canal conveyance, groundwater exploitation, field irrigation, etc., were collected with support of the Heihe plan (i.e. a key research plan "*Integrated Research on Eco-hydrological Process of Heihe River basin*" (US $ 23 million) by National Science Foundation of China). A MODFLOW-based three-dimensional (3D) groundwater flow model was established for Zhangye basin (a sub-basin in middle oasis) during 1991–2010. It included improved description of sources from irrigation based on detailed agro-hydrological modeling analysis. The major objectives were to reproduce the spatiotemporal groundwater dynamics over a long-term period (1991–2010) and to identify the main impact factors, and to foresee the possible strategies for recovery of groundwater tables in oasis areas. The research findings can be applied to similar oasis in other inland river basins in arid northwest China.

2. Materials and methods

2.1. Study area

2.1.1. Location, geography and climate

The middle oasis is defined as the region between the Yingluo gorge and Zhengyi gorge, consisting of four sub-basins (i.e. Zhangye, Jiuquan East, Jiuquan West and Shandan) (Fig. 1). It is one of the most important grain and seed production bases in northwest China. It consumes more than 90% of available surface water from the Heihe River, and contributes approximately 90% of agricultural production value of HRB. The mainstream of Heihe River mainly flows across the Zhangye basin (38.6°–39.8°N and 99.2°–100.8°E) which has the largest irrigated agriculture in middle oasis. In addition, the Zhangye basin is a closed basin with relatively distinctive hydrogeological boundary conditions (Wen et al., 2007; Hu et al., 2007; Zhou et al., 2011). In this study, the Zhangye basin was thus chosen as the simulation domain for groundwater modeling and long-term dynamic assessment (Fig. 1). Huge amounts of data were available from the Heihe plan as presented in Table 1, related to hydrology, hydrogeology, agriculture, land use pattern, etc.

The Zhangye basin covers the main area of three counties of Ganzhou, Linze, and Gaotai, covering an area of 5500 km^2. It is bounded by Qilian Mountain to the southwest and Longshou Mountain and Heli Mountain to the northeast (Fig. 1). There are two typical topographies, i.e. alluvial-proluvial fan in front of Qilian Mountain and river valley fine-soil plain (Fig. 2). The topography has a slope of 40‰ for alluvial-proluvial fan, and became flat in fine-soil plain with an average slope of 2‰. Land surface elevation ranges from 860 m and 2300 m above sea level (asl) in the northeast plain area and the southwest mountain-front area, respectively. The study area has a typically arid continental climate. Precipitation is about 140 mm per year mainly occurring in the summer season, whereas the mean annual evaporation (20 cm pan) reaches to 2050 mm.

2.1.2. Geology and hydrogeology

The Zhangye basin is underlain by Quaternary sediments, mainly the diluvium and alluvial deposits. The aquifer system mainly includes the stratum of Holocene (Q_4), Upper Pleistocene (Q_3) and Middle Pleistocene (Q_2) (Fig. 2). The stratum for Early Pleistocene (Q_1) is composed of consolidated sediments, forming the non-permeable bottom boundary for the Quaternary aquifer system. In the alluvial-proluvial fan, the Q_4 stratum is mainly composed of alluvium finer soils, sandy gravels and gravels, with thickness ranging at 5–30 m. The deposits for underlain Q_3 and Q_2 are the well-sorted pebbles, gravels and sand-gravels, with thickness of 50–100 m and 150–200 m, respectively. In fine soil plain, the deposits for Q_1, Q_3 and Q_4 are similar to that in the alluvial-proluvial fan, but with finer texture. However, the Q_2 stratum has more complex deposits, i.e., gravels and sand-gravels interlaced with two low-permeable layers (clay or loam clay, about 5–20 m thickness for each layer). Thus, on the basis of the properties of stratum deposits, a single-layer water-bearing stratum is identified at the alluvial-proluvial fan in front of mountain areas. Meanwhile, the multi-layer water-bearing strata are defined for the fine-soil plain, including interlaced two low-permeable layers for Q_2.

The Heihe River and its main tributary, Liyuanhe River, are two main rivers in Zhangye basin, with average annual runoff of 1.59 billion m^3 and 0.23 billion m^3, respectively. The annual runoff for each of other five tributary rivers is only about 0.011–0.04 billion m^3. Except for the Heihe River, surface runoff in other rivers is intercepted by reservoirs, and diverted for irrigation. Note that the six tributary rivers mainly recharge the groundwater as they are intercepted at mountain front (Fig. 1). However, the river seepage is too small and is generally negligible (Hu et al., 2007; IGGS, 2002). For the Heihe River, the river water strongly recharges groundwater in upstream front-mountain area with deeper groundwater depths (GWDs) through seepage, i.e. with seepage of 0.15 billion m^3 per year from the Yingluo gorge to Heihe bridge (Hu et al., 2007; IGGS, 2002). Then the complicated and strong exchanges (seepage, base flow and spring) take place in the valley plain area (with shallower GWDs). Irrigation water diverted from the Heihe River would largely recharge the groundwater system and finally return back to the Heihe River in spring and lateral flow. The annual groundwater recharge to Heihe River is about 0.7 billion m^3 during 1980s (IGGMED, 1982; IGGS, 2002), as estimated using isotope and temperature tracer. However, it becomes smaller as groundwater level declines in the past 20 years. For instance, the flux of a typical spring has decreased from 129.6 $L\,s^{-1}$ in 1986 to 51.0 $L\,s^{-1}$ in 2011.

2.1.3. Water use conditions and crop planting

There are totally seventeen irrigation districts in Zhangye basin (Fig. 3a), including twelve fed by Heihe River, one fed by Liyuan River and the rest smaller ones in the front-mountain area. The amount of irrigation water is kept at 1.6–1.7 billion m^3, accounting for over 90% of the total water use in the basin. Due to EWDP, irrigation water diverted from the river was reduced from 1.65 to 1.35 billion m^3 from 1990s to 2010s, while the water pumped from aquifers increased from 0.15 to 0.35 billion m^3 (Fig. 3b). The total irrigation water use remained almost the same due to various reasons related to technique and management issues (Jiang et al., 2015; Jiang, 2017). The number of groundwater pumping wells were less than 2000 in 1991 but increased to more than 8000 in 2012 in the basin. The irrigation water use per unit area actually decreased, mainly because of the large investment in canal systems construction (i.e. canal lining and water project regulation) and cease of intercropping (Fig. 3c–f). Up to 2011, the percentage of lined canal respectively reached to about 85% and 80% for main canals and tributaries, respectively, which effetively reduced the canal loss and seepgae. However, the farmland area has expanded from 90,000 ha to 150,000 ha during 1991–2010, which resulted in little change in total amount of irrigation water. A continuous decrease was observed for areas of grass, forest, water and bare land. Meanwhile, the amount of water for industrial and domestic use increased from 0.05 to 0.09 billion m^3, which was almost entirely from groundwater pumping. Some part of diverted river water was also applied to eco-environment sector, increasing from 0.05 to 0.09 billion m^3 after the application of EWDP. Overall, the total water use for all sectors in Zhangye basin varied slightly around 1.8 billion m^3 during 1991–2010.

Table 1
Information of the dataset collected for the construction of groundwater model in Zhangye basin.

Classification	Collected data
Hydrogeology data	Two typical hydrographic cross sections [a] Spatial distribution of hydrogeological parameters: hydraulic conductivity and specific yield [b] Pumping test data and layer texture for 30 boreholes [a] 8848 groundwater exploitation wells: location and volume for 2010 [c] Surface elevation at resolution of 1000 m [c] Map for location of fault and hidden fault [c]
Observation data	50 observation wells: location and ten-days groundwater levels from 1984 to 2010 [c]
Weather data	3 stations: rainfall, temperature, sunshine hour, relative humidity, and 20 cm pan evaporation for each month from 1984 to 2010 [d]
Hydrological data	Land use data for the late 1980s, 2000, 2005, 2007 and 2011[c] 3 hydrological gauging stations at the mainstream of Heihe River (Yingluo, Gao'ai, and Zhengyi gorges): monthly runoff and river level data from 1990 to 2010 [c] Annual runoff for the tributaries of the Heihe River [c] Investigated spring flow flux in 1984 [a] Monthly flux of two observation springs from 1984 to 2010 [e] Phreatic evaporation data for different groundwater depths [a] Measurement data of the hydrological sections in the middle Heihe River basin [c]
Agricultural data	Spatial distribution for 17 irrigation districts and their canals [c] Annual water use data for all irrigation districts from 1984 to 2010, including surface water and groundwater [e] Daily irrigation data at the main canal, branch canal, sub-lateral canal and farm canal scale [e] Daily groundwater exploitation data for typical irrigation districts [e] Lining data: spatial distribution of the lining length of main canals and branch canals from 1984 to 2010 [c] Statistic crop pattern data from 1984 to 2010 [e] Annual canal conveyance loss data from 1984 to 2010 [e] Daily canal conveyance data for some irrigation districts in 2003, 2004, 2005 and 2012 [c]

[a] Note: the data are obtained from IGGS (2002) and IGGMED (1982).
[b] Note: the data are obtained from Wen et al. (2007).
[c] Note: the data are obtained from the Cold and Arid Region Science Data Center.
[d] Note: the data are obtained from the China Meteorological Data Service Center.
[e] Note: the data are obtained from Zhangye-MY (2010).

The cropping pattern has changed greatly during the last three decades. The main crop changed from forage corn and wheat in 1990s to grain corn after 2000. The area for wheat reduced significantly and the intercropping pattern was almost abandoned. The remaining irrigated areas also included other croplands (e.g. planted with wheat, barley, cotton, cabbage, tomato and pepper) and some scattered grasslands and woodlands. Silt loam and loam are widely distributed in the cultivated farmlands, while coarse-textured soils are also typical in northeast area of downstream basin. Surface (basin) irrigation is the common method. There are generally 4–5 irrigation events during crop season (April–September), and also a winter irrigation in November for maintaining appropriate soil moisture conditions for seedling growth in the subsequent spring. Field deep percolation is relatively large due to the large irrigation amount, with relatively large variation in space and time.

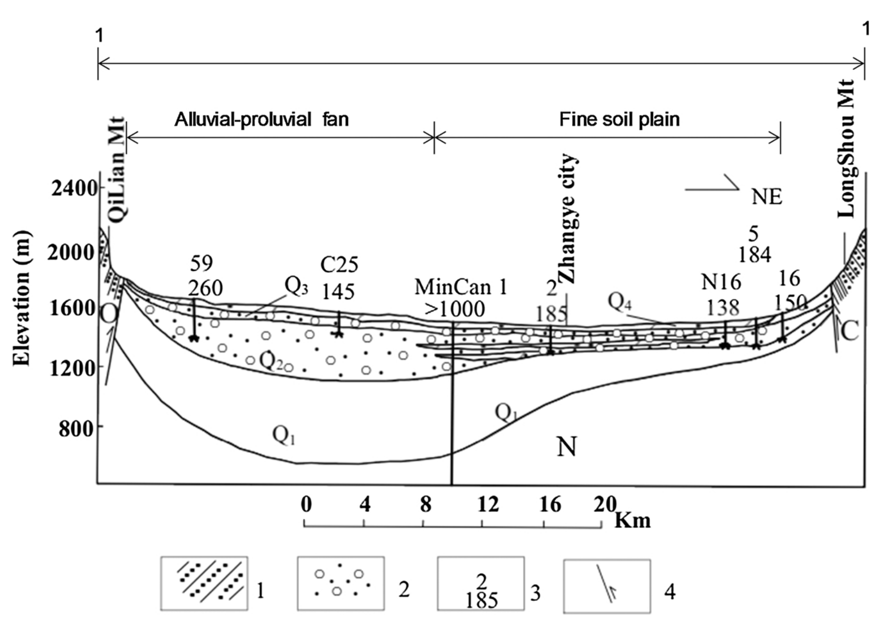

Fig. 2. Stratigraphic section across the Zhangye basin (adjusted from Hu et al. (2007)). 1 represents the layer is composed of loam clay or clay; 2 represents the layer is composed of gravels and stones; 3 represents the number and depth of bole hole; 4 represents the fault.

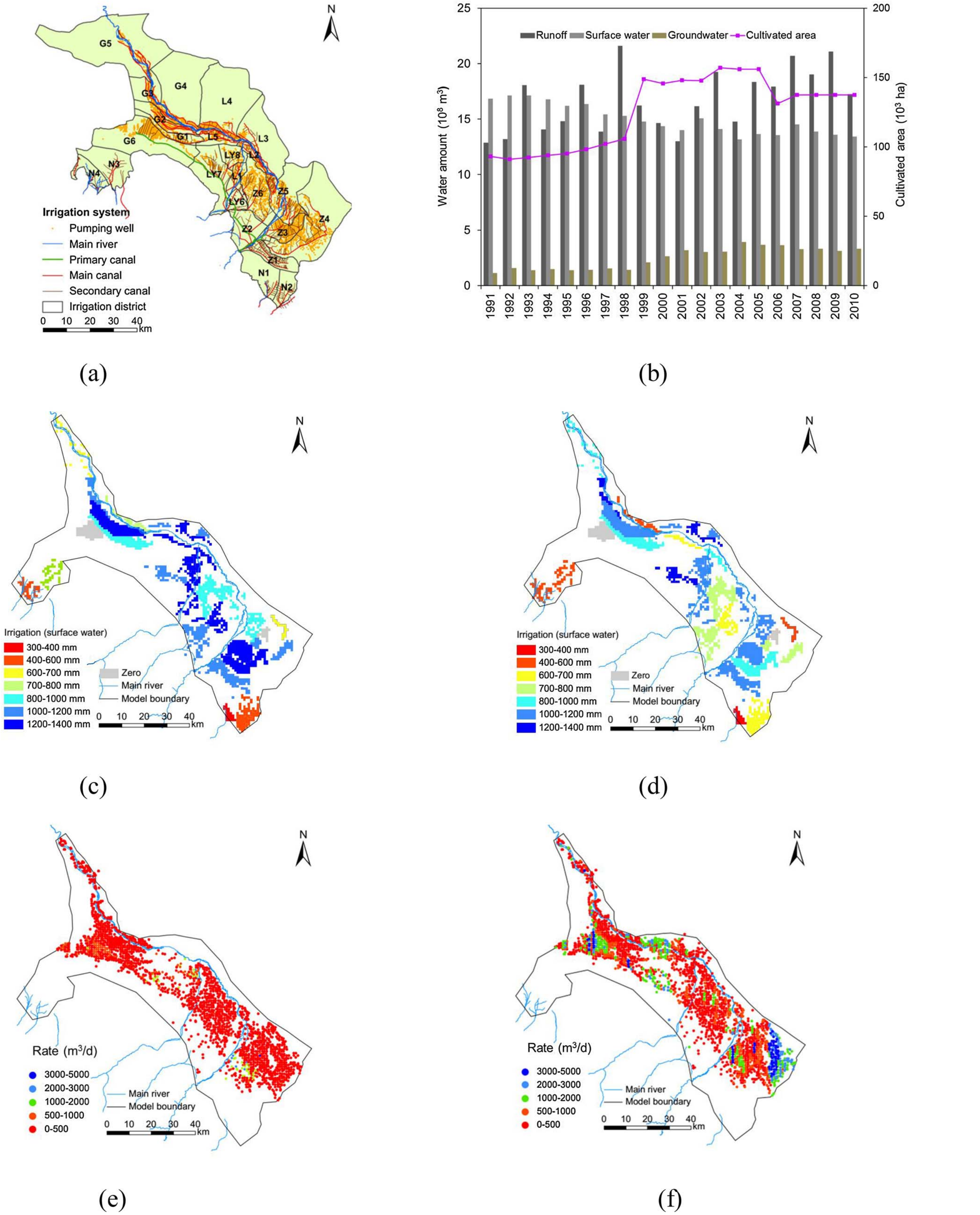

Fig. 3. Irrigation and land use conditions in Zhangye basin: Irrigation system distribution (a), irrigation water and land use changes during 1991–2010 (b); irrigation depth (diverted from surface river water) in two representative years of 1994 (c) and 2004 (d); and average daily rate of groundwater exploitation for irrigation in 1994 (e) and 2004 (f) (the exploitation rate was an integrated value on a 1 km grid cell).

2.2. Model description

The MODFLOW 2005 was utilized to develop the groundwater flow model of the Zhangye basin, with reasonably considering the recharge from field irrigation determined by using an ago-hydrological model (SWAP-EPIC). MODFLOW is a modular 3D model that includes modules to simulate steady-state or transient groundwater flow in confined/unconfined aquifers (Harbaugh, 2005). The model is based on solving the 3D partial differential equation of groundwater flow using the finite-difference method. The governing equation for groundwater flow is as follows:

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right)+W = Ss\frac{\partial h}{\partial t} \tag{1}$$

where K_{xx}, K_{yy}, K_{zz} are values of hydraulic conductivity along the x, y, z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity ($\mathrm{L\,T^{-1}}$); h is the groundwater level (L); W are the source/sink terms, with $W < 0$ for flow out of the groundwater system, and $W > 0$ for flow into the system ($\mathrm{T^{-1}}$); S_s is the specific storage of the porous material ($\mathrm{L^{-1}}$); and t is time (T). The source code of MODFLOW is open and easily accessible. Various packages have been readily incorporated into the MODFLOW to treat the different boundary conditions and the source/sink terms, typically as the packages of Recharge (RCH), Well (WEL), River (RIV), Drainage (DRN) and Evapotranspiration segments (ETS). MODFLOW has become a powerful and widely used tool in hydrological or hydrogeological competition research and groundwater management.

Particularly, the SWAP-EPIC model was used to help describe the spatiotemporal recharge from field irrigation, which was the main source for groundwater with the most uncertainties in Zhangye basin. SWAP-EPIC was a one-dimensional (1D) physical-based agro-hydrological model that could simulate soil water flow, solute transport and crop growth on a field scale and daily time-step (Xu et al., 2013). Soil water flow and solute transport were described based on the vertically 1D Richards′ equation and advection-dispersion equation, respectively. Crop growth and yield were calculated using the modified EPIC crop growth model. More detailed calculation principles for SWAP-EPIC could be found in Xu et al. (2013). Meanwhile, the GIS-based SWAP-EPIC has been proposed for simulating the regional agro-hydrological processes in a distributed manner by Jiang et al. (2015). With the spatial combination of various soil, crop, climate, irrigation conditions, the calibrated GIS-based SWAP-EPIC could provide the reasonable estimation of distributed deep percolation. For avoiding the computation complexity, we did not directly run the SWAP-EPIC for the whole simulation period. A more reasonable alternative was adopted in this study, i.e. to estimate the recharge coefficients from field irrigation and precipitation (ξ) for different conditions based on modeling results. The ξ values often had strong variations with different soils, irrigation depths and plants (Sophocleous, 2004; Jiang, 2017). SWAP-EPIC was applied to estimate the ratio of deep percolation to field irrigation and precipitation (i.e. D_p ratio) in irrigated areas with different soil, irrigation and plant conditions. When assuming that the deep percolation water could finally recharge to the groundwater, the D_p ratio should be close to ξ. That is, the approximate relationship between ξ and the sum of irrigation depth and precipitation could be systematically obtained for irrigated areas. Thus, this approach could provide more accurate and reasonable estimation of recharge from field irrigation for MODFLOW use. Also, the other modeling researches could directly and conveniently use the recommended ξ values to estimate the groundwater recharge with no need to develop and run the distributed agro-hydrological models.

2.3. Numerical hydrological model, calibration and validation

The domain was discretized into 5 layers, according to the lithology of sediments and aquifer characteristics. The first layer was the phreatic aquifer, including strata of Q_4, Q_3 and the Q_2 part above the first low permeable layer of Q_2. The second and fourth layers were both composed of low permeable stratum of Q_2 in the northeast and permeable stratum in the southwest. The third layer was defined as the aquifer between above two layers, i.e. two low permeable strata of Q_2 in the northeast and two permeable strata of Q_2 in the southwest. The fifth layer was the aquifer consisting of the lower part of Q_2. The Q_1 with the consolidated sediments (i.e. bedrock) was defined as the non-permeable bottom for the model domain. That is, the fifth layer was located between the second low permeable sediments of Q_2 and consolidated sediments in Q_1. A uniform grid with square cells of 1000 m was adopted, i.e. 160 rows and 155 columns in horizontal direction. The monthly stress period with 10 time steps in each was adopted in model simulation. The hydrogeological parameters were set up based on the geologic and hydrogeological reports and literature from previous researches (IGGS, 2002; Wen et al., 2007) (mainly including bore hole and pumping test data). Conductivity in horizontal direction was set as the same while the conductivity in vertical direction was set up as 10% of that in horizontal direction. The specific yield (S_y) for phreatic aquifer was set according to the pumping test. Its values varied between 0.15 and 0.30, with relative high value (0.4–0.5) set up near the area where the spring spilled out. The storage coefficients for confined aquifer were set between 0.00001 $\mathrm{m^{-1}}$ and 0.0001 $\mathrm{m^{-1}}$.

2.3.1. Initial conditions and lateral boundary

Initial values of groundwater levels were obtained using the ordinary kriging interpolation technique applied to the observation data of 50 wells at the beginning of 1991, which was also adjusted by adding some control points according to the groundwater flow field reported by other researches (Wen et al., 2007; Yao et al., 2015b; Hu et al., 2007). Thus, a reasonable smooth spatial distribution of the groundwater levels was achieved.

Lateral A–B and C–D (Fig. 1) were both defined as the Neumann boundary conditions, and the flux was respectively estimated to be −0.01 billion $\mathrm{m^3}$ and 0.1 billion $\mathrm{m^3}$ using the Darcy's law. No-flow boundary condition was defined for both B-C and D-E, as there were thrust faults and hidden faults along the two boundaries. A-E was also defined as no-flow boundary where the hydraulic connection with Yanchi basin was cut off by the Yulin mountain uplift.

2.3.2. Other boundary conditions and sinks/sources

2.3.2.1. Recharge from irrigation, precipitation and spring discharge. Groundwater recharge from field irrigation and precipitation (R_{firg}, L) for irrigated areas was calculated as follows:

$$R_{firg} = I_r{*}\xi \tag{2}$$

where I_r is the irrigation depth (L). The ξ values can be inferred from the results of an agro-hydrological modeling in the Zhangye basin by using process-based SWAP-EPIC model in our previous studies (Jiang et al., 2015; Jiang, 2017). The model was firstly calibrated by using the observed soil and crop data in 23 field sites (with five soil types and four crop species) of Yingke Irrigation District during 2012 and 2013 (Jiang et al., 2015). Then, it was further extended to be used on the scale of Zhangye basin, and validated with the remote sensing evapotranspiration (Jiang, 2017). Simulation results could provide the reasonable deep percolation for whole Zhangye basin, covering different crops and soil types under various irrigation depths. This modeling could provide the reasonable values of D_p ratio at 200 cm soil depth, covering different combinations of soils, crops, natural plants and irrigation depths in Zhangye basin. The ξ value could be seen close to the D_p ratio value with relatively deep groundwater depth. Its values for various land use, soil types and irrigation depths are summarized and given in Table 2.

Groundwater recharge from canal seepage (R_c, L) was calculated as

Table 2
Potential coefficient (ξ) of recharge from irrigation related to different irrigation depth, crops and soil types. The "/" means that no such conditions exist.

Irrigation (mm a^{-1})	ξ_ for loamy soil				ξ_for sandy soil			
	Field corn	Seed corn	Wheat	Forest/Grass	Field corn	Seed corn	Wheat	Forest/Grass
700–800	0.3–0.35	0.33–0.4	/	/	0.33–0.38	0.4–0.45	/	/
600–700	0.23–0.30	0.25–0.33	/	/	0.27–0.33	0.32–0.4	/	/
400–600	0.15–0.23	0.17–0.28	0.33–0.45	/	0.19–0.27	0.19–0.32	0.4–0.5	/
300–400	0.10–0.15	0.15–0.16	0.25–0.33	0.07–0.0.09	/	0.10–0.16	0.25–0.4	0.12–0.2
200–300	/	/	0.15–0.25	0.05–0.08	/	/	0.12–0.2	0.08–0.16

Note: Loam soil, silt loam soil and sandy loam were classified into loamy soil, while sandy soil and sandy loam soil were classified into sandy soil for better application.

follows:

$$Rc = Qs^{*}\delta*\varepsilon \tag{3}$$

where Q_s is the canal conveyance loss (L), δ is the ratio of canal seepage to canal conveyance loss (−), and ε is the ratio of groundwater recharge to canal seepage (−). Annual data of canal conveyance loss were obtained from Zhangye-MY (2010). The values of δ *and* ε were available from the previous hydrogeological reports (IGGMED, 1982; IGGS, 2002).

Groundwater recharge from precipitation infiltration for the non-irrigated areas (R_p, L) was calculated as follows:

$$Rp = P_e^{*}\alpha \tag{4}$$

where P_e is the effective precipitation (L) only considering a single rainfall over 10 mm (IGGS, 2002), and α (−) is the coefficient of precipitation recharge and affected by land cover, soils and the size of rainfall event. α value was set small (0.05–0.08) in the mountain-front area with deep GWDs. It became larger in the plain area (i.e. 0.08–0.20), increasing with the coarser soil texture and larger rainfall event (IGGS, 2002; IGGMED, 1982).

Discharge by spring effluence mainly occurred at the edge of alluvial-proluvial fan and areas along the Heihe River after the Heihe bridge (see Fig. 1) (Zhao et al., 2010). The total volume was estimated to about 0.7 billion m^3 in 1980s and decreased to about 0.4 billion m^3 in 2010s (IGGS, 2002; IGGMED, 1982). It could be defined as the areal discharge. The location and flux were defined according to the hydrogeological surveys and reports and the observation data of a typical spring in the basin (IGGS, 2002; IGGMED, 1982). Finally, the recharge flux from irrigation and rainfall and the discharge flux from spring effluence were incorporated together by using the RCH package.

2.3.2.2. Groundwater exploitation. A large number of pumping wells were defined to describe the groundwater exploitation using the WEL package. The number of wells increased from less than 2000 in 1991 to over 8000 in 2011, with total volume increasing from 0.1 to 0.45 billion m^3 (Zhangye-MY, 2010). Detailed information of the pumping wells were collected from the latest survey in 2010, including location, construction time, water use, well depth, exploitation volume, screen materials, etc. Pumping schedules for agricultural wells were determined as referred to the irrigation schedules (Zhangye-MY, 2010) in the basin, while pumping schedules for industrial and domestic wells were averaged annually. Pumping wells in a model cell (1000 m × 1000 m) were integrated into an equivalent well when using the WEL package, and thus 1885 wells were finally defined in the modeling.

2.3.2.3. Groundwater evaporation. Piecewise linear decreasing function was applied to describe the groundwater evaporation (E_{gw}) using the ETS package. The relationship between evaporation rate and GWD was obtained from the previous experiments for different soils and land covers (bare soil, cropland, grassland and forestland) (IGGS, 2002). Based on this, four pieces of linear equations were determined in ETS package. The extinction depth and maximum groundwater evaporation rate were set according to different types of soils and land use, and also defined according to the experiments and previous literature (IGGS, 2002; IGGMED, 1982). Such as, extinction depths for bare land, cropland, grassland and forestland were 7–10 m, 5–10 m, 5 m, and 15 m, respectively, with different soil types and species. The range of maximum groundwater evaporation for bare land was set as 300–500 mm a^{-1} for different soils, and that for cropland, grassland and forestland was respectively 200–300 mm a^{-1}, 400–600 mm a^{-1} and 500–1500 mm a^{-1} as affected by vegetation density (IGGMED, 1982; IGGS, 2002).

2.3.2.4. Water exchange between river and groundwater. The main Heihe River was defined using the RIV package. The length of Heihe River in the Zhangye basin was about 180 km, and three hydrological stations were established to gauge the runoff and water levels in the Heihe River, located at Yingluo gorge, Zhengyi gorge and Gaoai gorge. Detailed monthly river levels of the three stations were collected and applied in the model. Elevation of the river bed and river width was set up based on the previous survey (Ma et al., 2011). The thickness of the relative impermeable layer was set as 3 m. River bed seepage coefficients was set between 1 m d^{-1} and 0.1 m d^{-1}. The value of 1 m d^{-1} was used in the alluvial-proluvial fan while 0.1 m d^{-1} was used in the fine soil plain according to the previous studies (Zhou et al., 2011; IGGMED, 1982; IGGS, 2002). The Liyuan River was defined as areal recharge along the Liyuan River. The other 5 rivers were ignored since their surface runoff was very small after the irrigation diversion.

2.3.3. Calibration and validation

The monthly GWL data from 50 observation wells (during 1990–2010) were used to calibrate and validate the model. The simulated GWLs were thus aggregated into the monthly values for comparison. The data in 1990 were used for warming up the model. The observed dataset in 1991–2000 and in 2001–2010 were respectively applied for model calibration and validation. Parameters referring to the hydraulic conductivity and specific yield were calibrated through an iterative process using a trial-and-error method, due to they were relatively uncertain in the study area. The root mean squared error (RMSE), Nash and Sutcliffe model efficiency (NSE), coefficient of determination (R^2) were used as indicators of goodness of fit (Legates and McCabe 1999; Moriasi et al., 2007). Their definitions can be referred to Xu et al. (2013).

3. Results and discussion

3.1. Model calibration and validation

Comparison between the simulated and observed GWLs for all 50 observation wells during the simulation period 1991–2010 are described in Fig. 4. Spatial distribution of the main calibrated hydrogeological parameters (i.e. K_x and S_y) is presented in Fig. 5. Results showed that the simulated GWLs matched well with the observed ones both for calibration and validation. These produced a RMSE = 2.6 m, a NSE = 0.999 and a R^2 = 0.998 during calibration period (1991–2000).

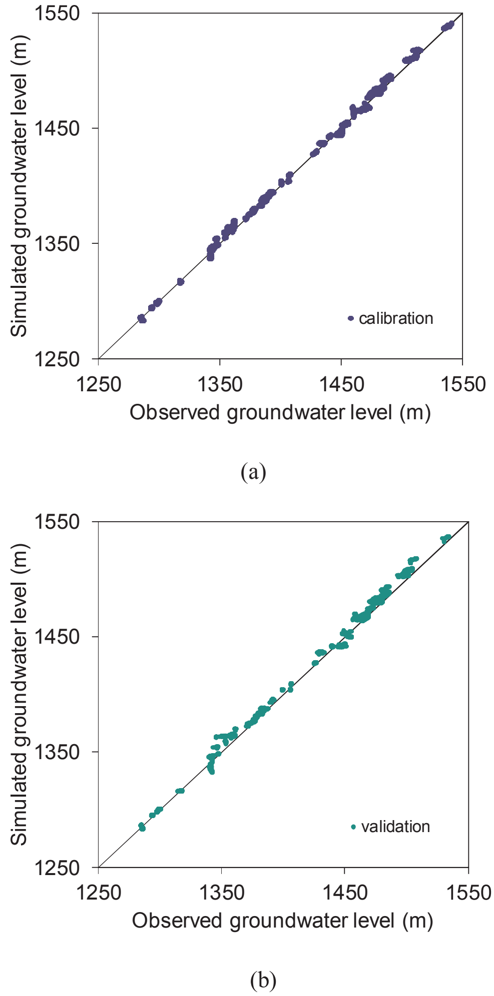

Fig. 4. Comparison between simulated and observed groundwater levels of 50 wells for calibration period (a) during 1991–2000 and validation period (b) during 2001–2010.

Similar fitness values were also obtained during validation period (2001–2010), with RMSE = 3.9 m, NSE = 0.996, and R^2 = 0.998.

Note that the 50 observation wells have different change trends as they were distributed in areas with different geomorphology, land cover, GWD and water use structure. Our modeling could well describe the various trends of GWL fluctuations (Fig. 6), typically as: continuous decreasing trend (e.g. well 7), relatively stable trend (e.g. wells 16, 17, 23 and 26), and the decreasing and then increasing trend (e.g. wells 1, 8 and 10). The third trend was rarely captured in previous modeling studies, partly due to the over-simplification of recharge from irrigation. In addition, the wet, normal and dry years were all included in the simulation period. Thus, this further indicated that our present simulation results are reasonable and convincing.

We also noted that, the simulated crests or troughs of GWLs occurred a little earlier or later than the observed ones for some wells in some years. This could be mainly attributed to the lack of detailed irrigation data during that year. Meanwhile, there was a relatively large difference between the simulated and observed GWLs for wells in mountain-front areas (e.g. around wells 7 and 34) (Figs. 1 and 6). It was caused by that the observation GWL data was limited and the hydrologic gradient was too high to get an accurate initial GWLs in those areas. Despite that, the inter-annual changes of GWLs were considered to be well captured in terms of long-term (20-year) simulation (Fig. 6). Overall, our calibrated model should be reasonable to simulate the groundwater dynamics for the Zhangye basin, and hence could be used as a useful tool to analyze the complicated groundwater behavior and to support the restoration of groundwater balance.

3.2. Groundwater dynamics

Model simulations provided detailed information about the spatial and temporal distribution of GWLs and GWDs for the period of 1991–2010 (Figs. 7 and 8). Groundwater mainly flowed from south to north in Zhangye basin. It received recharge in the upper parts of the Heihe River, and discharged into the Heihe River in the middle and lower stream in the north basin (Fig. 7). Gradient was large in the south part of the basin as well as along the Heihe River, while with very gentle slopes in the central plain part. Results indicated that GWLs had a main trend of declining during the past 20 years, with various changes in time and space (Figs. 6, 7 and 9). The average GWL for the whole basin had a continuously decreasing trend. Its decreasing rate was equal to $-9.5\ \mathrm{cm\ a^{-1}}$ from 1991 to 1995, $-8.5\ \mathrm{cm\ a^{-1}}$ from 1995 to 2000, $-9.4\ \mathrm{cm\ a^{-1}}$ from 2000 to 2005 and, $-7.8\ \mathrm{cm\ a^{-1}}$, from 2005 to 2010, respectively. Meanwhile, it was found that GWLs also rose up in some local part during the wet period 2005–2010 (Z3, Z5 and L1), with the abundant river runoff in these wet years and associated large irrigation applied in these wet years (Fig. 9). Nevertheless, for the areas with heavy groundwater exploitation, the decline rates of GWLs were still larger than that in the previous years (Z4 and G6) (Figs. 3 and 9). Note that the GWL change trends could be classified as three typically types and were described in detail in the following parts.

Relatively stable trend was found in irrigation districts along the Heihe River (e.g. around well 16, 17, 23 and 26) (Figs. 6 and 9), due to still relatively large irrigation and consequently significant recharge from irrigation as well as close water exchange with the Heihe River. There was often excessive river water diversion while almost no groundwater pumping, because of very convenient diversion conditions. This resulted in large amounts of vertical deep percolation or lateral water flow towards the Heihe River. Thus, the groundwater system was in an appropriate state here, with a small fluctuation of annual changes of GWLs. On the other hand, decreasing and then increasing trend was observed in the upper parts of the Heihe River and Liyuan River (e.g. around wells 1 and 8). Slight fluctuations were observed from 1991 to 2000. In those years, the reason for decrease could be attributed to the expansion of farmlands (i.e. doubled), almost depending on the over-exploitation of groundwater (i.e. increasing more than 3 times). However, since 2003, surface river runoff entering into Zhangye basin became larger, and subsequently more river water was diverted for irrigation in these major irrigation districts in upstream area. Meanwhile, the groundwater exploitation and the farmland area were nearly unchanged. Thus, these factors caused larger deep percolation and/or larger groundwater recharge, resulting in an increase in water table from 2005 to 2010 (Fig. 9). However, this restoration of GWLs was more induced by the increase in surface water in continuous wet years. Therefore, reasonable control of farmland area and groundwater management was still necessary in normal and dry years.

The more serious problem was that a continuously or even extremely decreasing trend occurred in the southeast (farmland in the Z4) and northwest parts (farmland in the G6) of the plain, where all of water use was from groundwater exploitation (typically as around well 7) (Figs. 6, 7 and 9). The decreasing rate even reached to $2\ \mathrm{m\ a^{-1}}$ at most in some years. The area of farmland was triple in 2010 as compared to 1990, meanwhile groundwater exploitation became twice as before. The decrease of irrigation depth for unit area resulted in the reduction of deep percolation and thus a decrease of groundwater recharge. Eventually, GWL decreased continuously from 1991 to 2010, and the decreasing rate was closely related to the total amount of groundwater exploitation. This might lead to an unfavorable condition for natural vegetation.

3.3. Critical GWDs: spatial and temporal distribution

The spatial distribution of GWDs at the end of year 1991, 1995, 2000, 2003, 2005 and 2010, respectively is presented in Fig. 8. GWDs

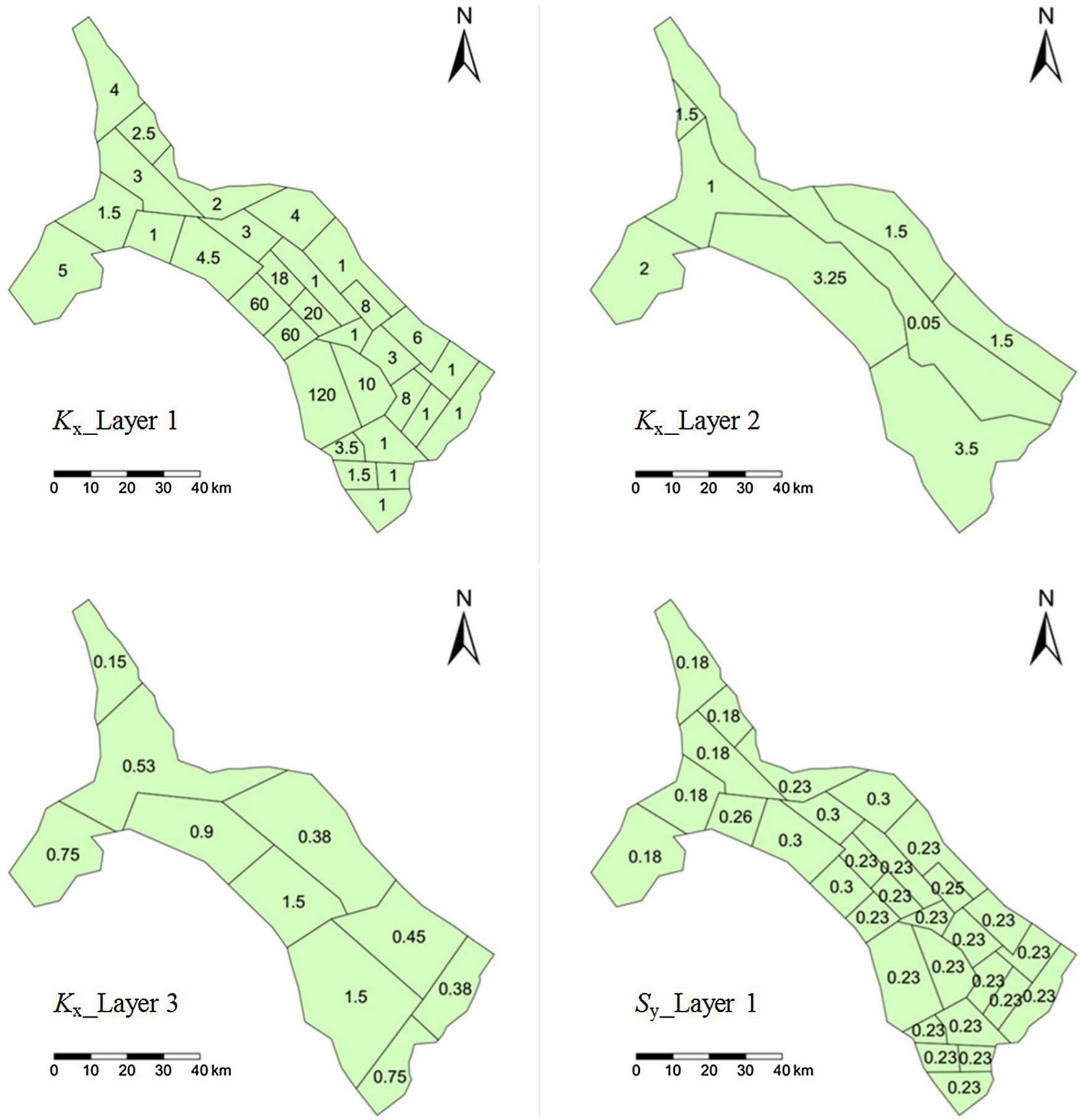

Fig. 5. Spatial distribution of the calibrated K_x and S_y in aquifers, with $K_x = K_y = 10\,K_z$ (m d^{-1}). K_x, K_y, K_z are the values of hydraulic conductivity along the x, y and z coordinate axes, and S_y is the specific yield.

were larger at the alluvial-proluvial fan along the north and south mountain-front area, ranging from 40 to 50 m to about 800 m. The increase in GWD during last 20 years was almost insignificant as compared with its large depths. In the fine-soil plain where the major agriculture area located, GWD varied from approaching ground surface to 30–40 m in space. The increase of GWD was relatively obvious considering its shallow characteristics in fine-soil plain, with the large increases of farmland area and groundwater exploitation. It should be noted that this increase may have significant effects on crops and natural vegetation. It was found that the GWD increase was particularly significant in the central parts of upstream basin (e.g. around LY8 and Z6), the parts on the north of Heihe River in downstream basin (main groundwater exploitation area, e.g. around G1, G2 and G6), and the parts along the Heihe River after the Heihe bridge (mainly spring overflow zone, e.g. around L2 and L5) (Figs. 3a and 8). For the central parts of plain area, GWD was about 1–5 m in the 1990s, and changed to be about 1–9 m in 2010. Especially, the area with GWDs of 1–3 m decreased significantly. In and around the spring overflow zone, the GWDs mainly ranged from zero to about 10–20 m, with a significant decrease of area with GWDs less than 3 m. This was also in agreement with the decrease of both the spring area and spring flux in field surveys (IGGS, 2002).

The GWD was an important indicator or symbol to reflect the health of eco-environment in arid areas. Thus, referring to previous studies (Guo and Liu, 2005; Wang et al., 2015; Wang et al., 2016), relationships between GWD and ecological characteristics in Zhangye basin could be classified as: species diversity decreased as GWD $>$ 5 m; vegetation coverage and biodiversity decreased significantly as GWD $>$ 7 m; and the structure of plant community became simple as GWD $>$ 9 m. The areas for GWD less than 5 m, 7 m and 9 m were calculated as shown in Fig. 10. They all decreased with the percentage of 38.3%, 34.7% and 33.7%, respectively during the past two decades. The change of these areas was closely related to the agricultural activities and climate change, corresponding to the GWL and GWD changes as described before. As shown in Fig. 10, a relatively higher decreasing rate was found from 1991 to 2003, due to the uncontrolled expansion of irrigated lands and groundwater pumping. The area and groundwater use increased from 9.3×10^4 ha to 14.6×10^4 ha and from $1.27 \times 10^8\,m^3$ to $2.9 \times 10^8\,m^3$, respectively, meanwhile, the river runoff and surface water diversion were at an average level. Gentle decreasing rate was

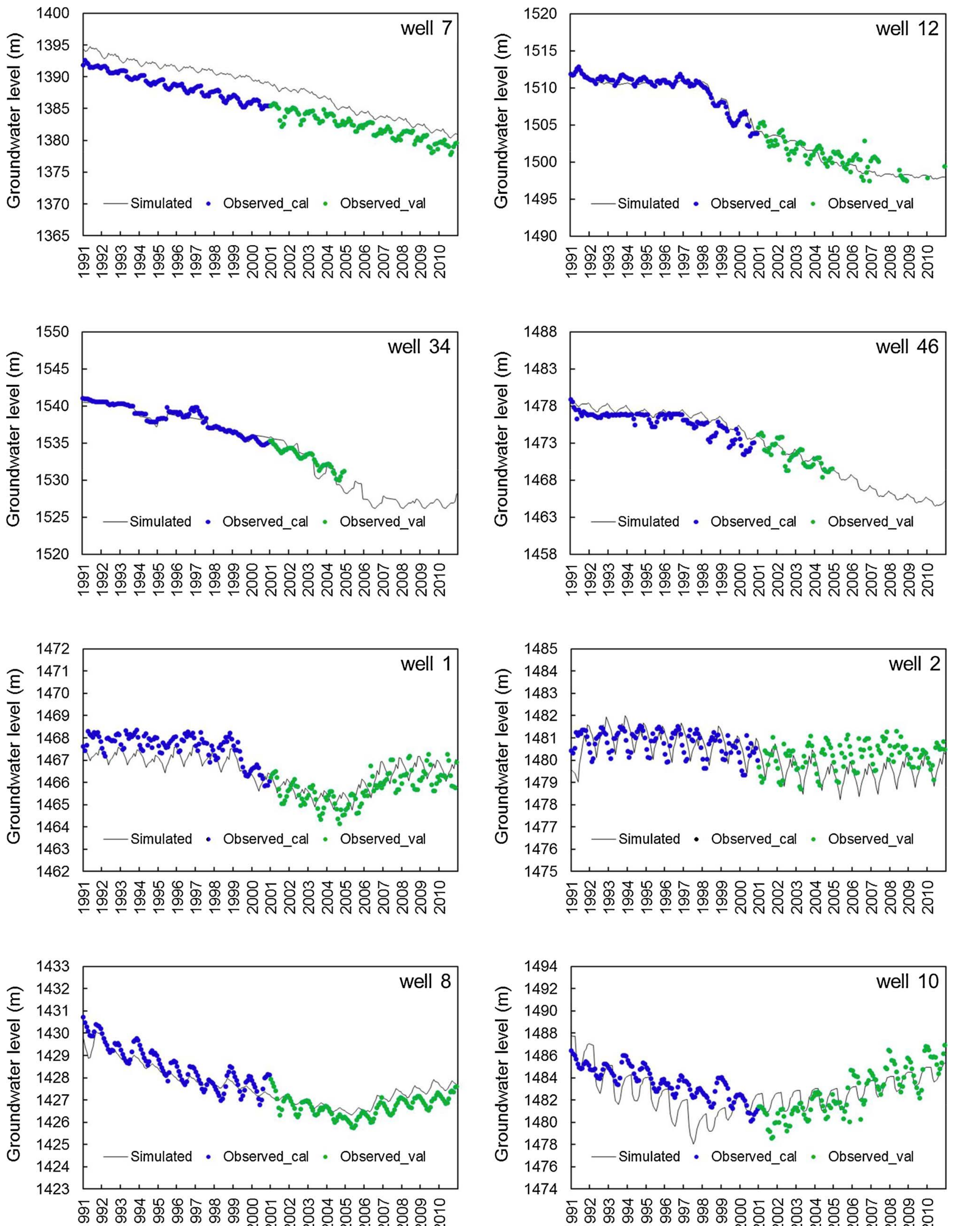

Fig. 6. Comparison between simulated (lines) and observed (points) groundwater levels in fourteen representative observation wells (Fig. 1). Observed_cal and observed_val represent the data for calibration period and validation period, respectively.

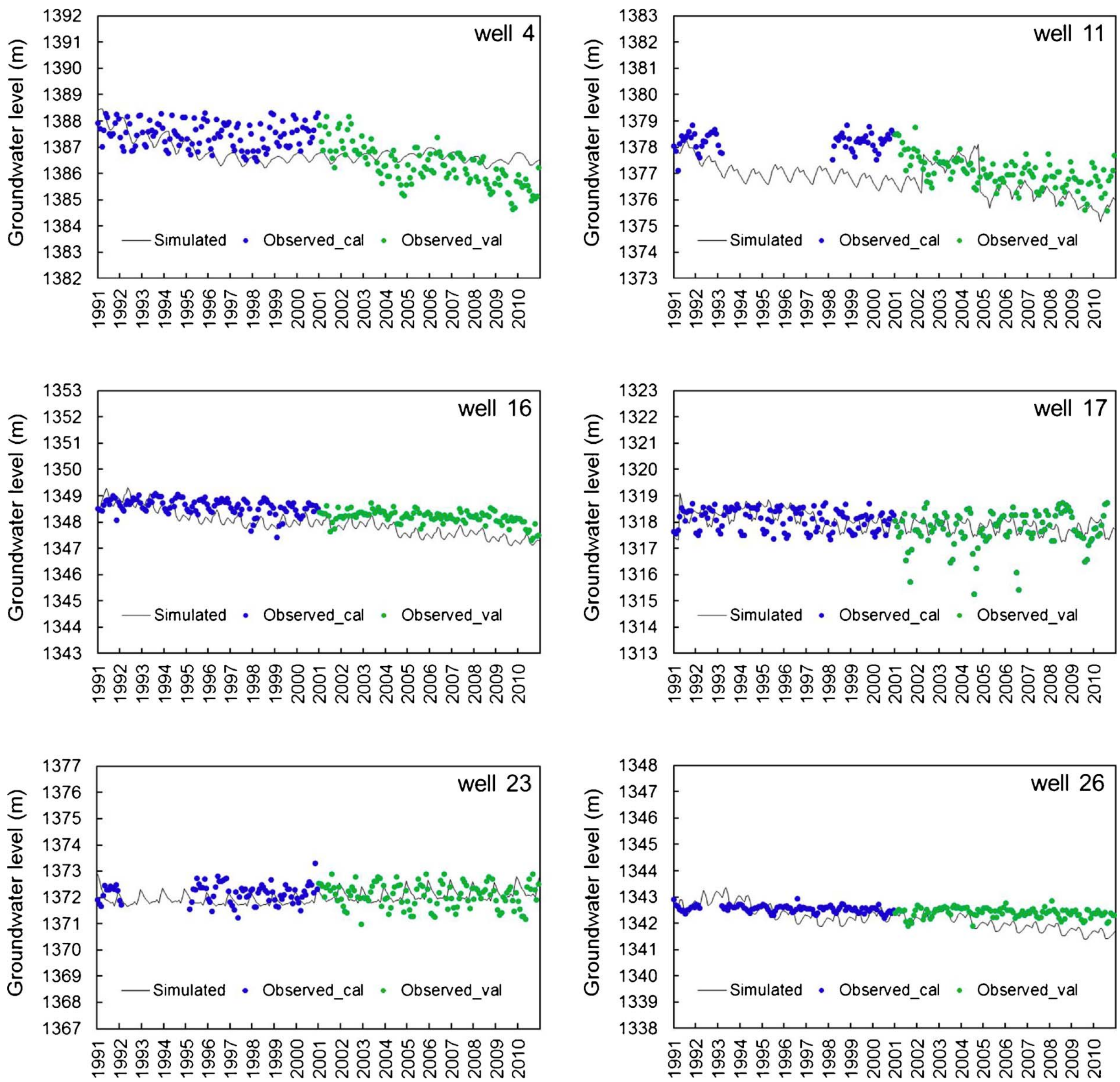

Fig. 6. (*continued*)

found from 2004 to 2010 because of the wetter climate (Fig. 10). During this period, more surface water recharged the groundwater system, the increments of groundwater pumping were smaller than those of the former years. The decrease of area with shallow water tables is consistent with the degradation of vegetation and wetlands in Zhangye basin (Guo and Liu, 2005). This implies that urgent measures should be taken for eco-environmental protection in this basin.

3.4. Water balance analysis

3.4.1. Regional scale

The groundwater balance was also analyzed in the simulation period. The average volume and the inter-annual changes of each balance term are presented in Figs. 11 and 12, respectively. Results showed that the groundwater balance in Zhangye basin was negative at $-2.7 \times 10^8\,m^3$ in average, varying at $-4.5 \times 10^8\,m^3$ to $-0.6 \times 10^8\,m^3$ during 1991–2010 except an extremely wet year with $0.11 \times 10^8\,m^3$. Recharge from irrigation water (i.e. from deep percolation and canal seepage) and river seepage were the main sources of groundwater recharge (Fig. 10), averagely accounting for 64.3% and 31.7% of the total recharge, respectively. Recharge from irrigation ranged from $7.2 \times 10^8\,m^3$ to $8.0 \times 10^8\,m^3$, whereas river seepage ranged from $1.5 \times 10^8\,m^3$ to $4.5 \times 10^8\,m^3$ (Fig. 12). The variations were closely related to the amounts of the river runoff entering the basin and the surface water diversion (Figs. 3 and 12). Recharge from precipitation was only $0.5 \times 10^8\,m^3\,a^{-1}$, accounted for about 3% of the total recharge.

Groundwater discharge mainly included spring overflow (S_{pr}), groundwater evaporation (E_{gw}), groundwater pumping (P_{gw}), and discharge to the rivers (D_{riv}) (Fig. 11), with their percentage equaling to 42.3%, 31.9%, 17.9% and 7.9%, respectively. The amount of S_{pr} was both affected by surface river runoff and groundwater exploitation. Except some wet years, it presented an obviously decreasing trend as compared with those in 1990s. E_{gw} decreased continuously with the continuous decline in GWL and areas with shallow water depths (Fig. 12). P_{gw} increased sharply during the simulation period. D_{riv} was maintained at around $1.0 \times 10^8\,m^3$ due to the intensive interaction with groundwater and relatively stable GWL in areas along the Heihe River. It was worth noting that the groundwater system was in a negative balance status even in wet years. This implied that GWL would decline continuously in the future if agricultural water use practices in the basin could not be well improved.

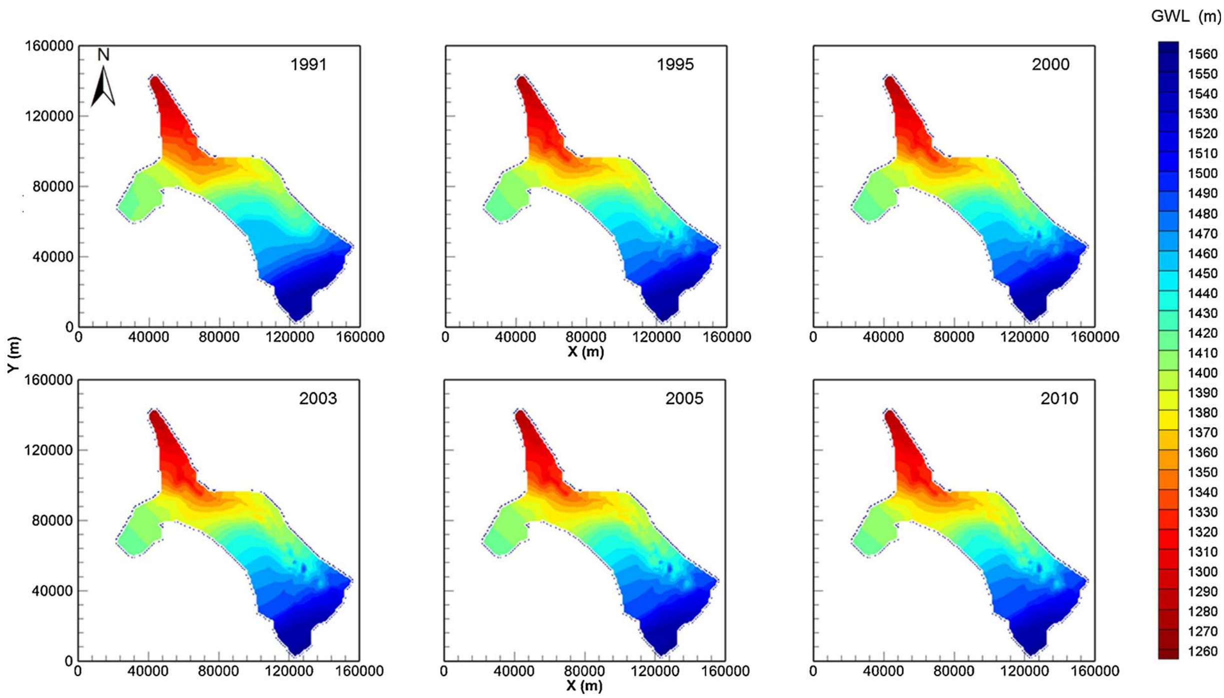

Fig. 7. Modeling results of groundwater levels (GWLs) at the end of year 1991, 1995, 2000, 2003, 2005 and 2010 of the top layer (phreatic aquifer) (groundwater heads among different layers are small and thus have very similar spatial distribution for lower layers).

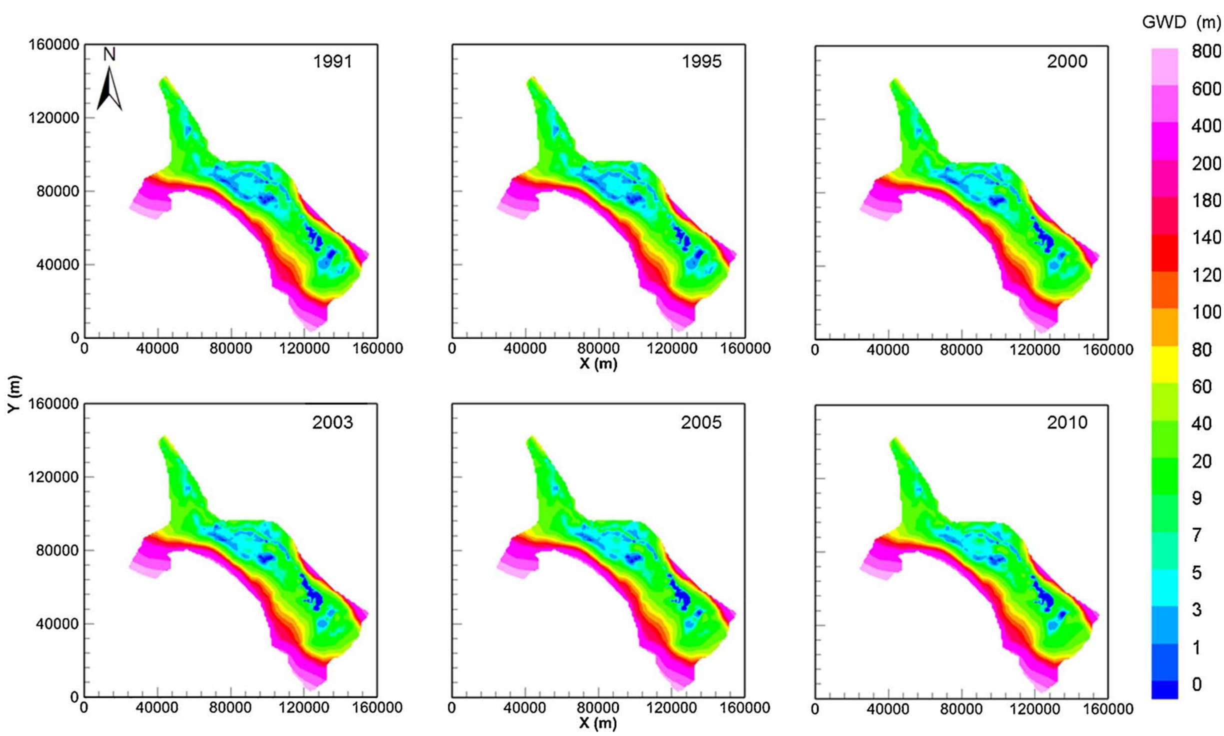

Fig. 8. Simulated distribution of the groundwater depths (GWDs) at the end of year (on December 31th) in 1991, 1995, 2000, 2005 and 2010.

3.4.2. Representative zone

According to the long-term GWL dynamics, four representative zones were defined in the basin (Fig. 13). Zone 3, zone 1, zone 2 and zone 4 were representative for the areas with sharp continuous GWL decline, slow continuous GWL decline, decreasing and then increasing GWL trends, and stable GWL trends, respectively. Total water use in zone 1, 2 and 4 was based on the joint use of groundwater and river water, while that for zone 3 was only from groundwater pumping. Groundwater balance of four representative zones is calculated and presented in Fig. 13. Results revealed that the average water balance for zone 3 was negative at −100 mm water depth per year, and the recharge amount was less than one third of discharge one. Groundwater funnel had appeared in zone 3 since 2000, with the affected area increasing in the following years. This caused obviously negative impact on local ecosystem. Zone 1 was also facing the similar problems but with less severe situation as zone 3. There used to be enough surface water for zone 1 during 1991–1997. Recharge from irrigation, being as the main recharge component for groundwater, was slightly larger than

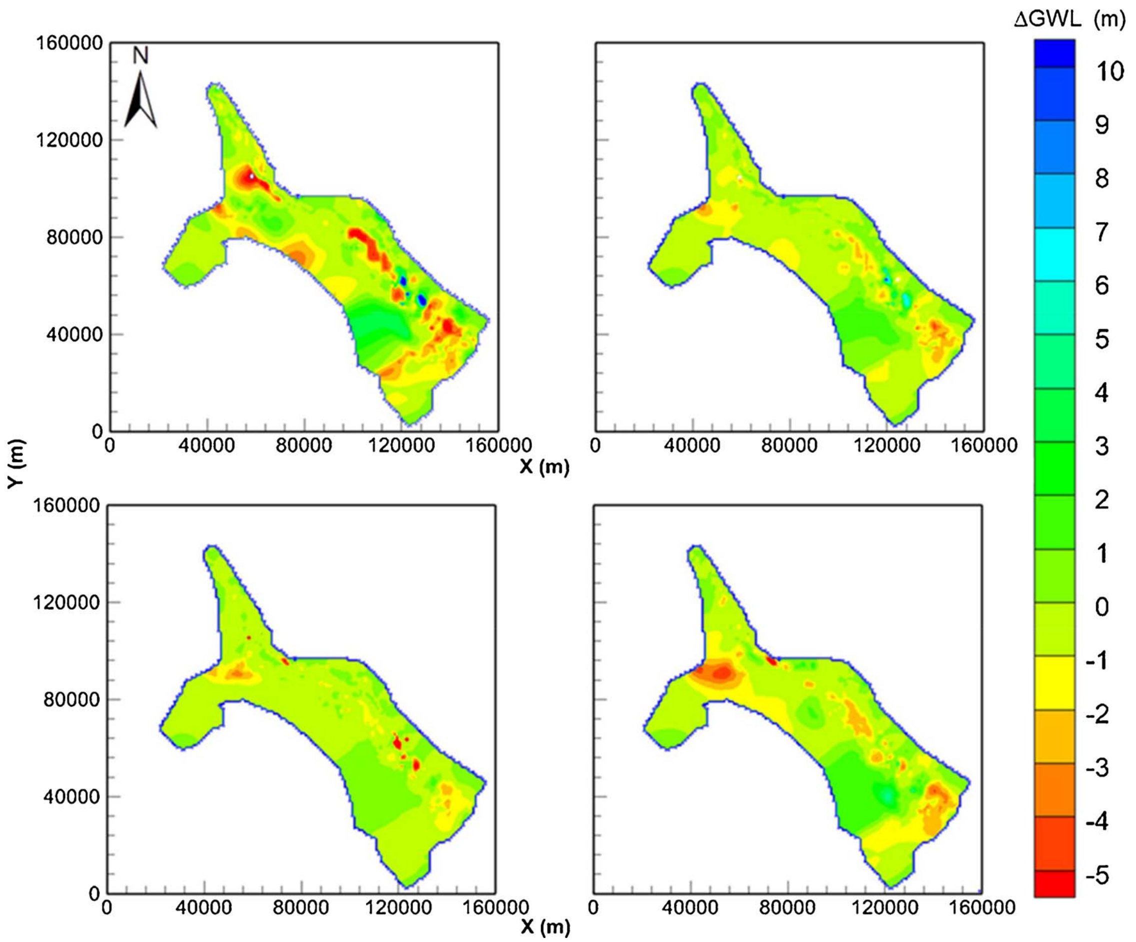

Fig. 9. Modeling results of the groundwater level change (ΔGWL) for the top layer in every five years: a (1995–1991), b (2000–1995), c (2005–2000) and d (2010–2005).

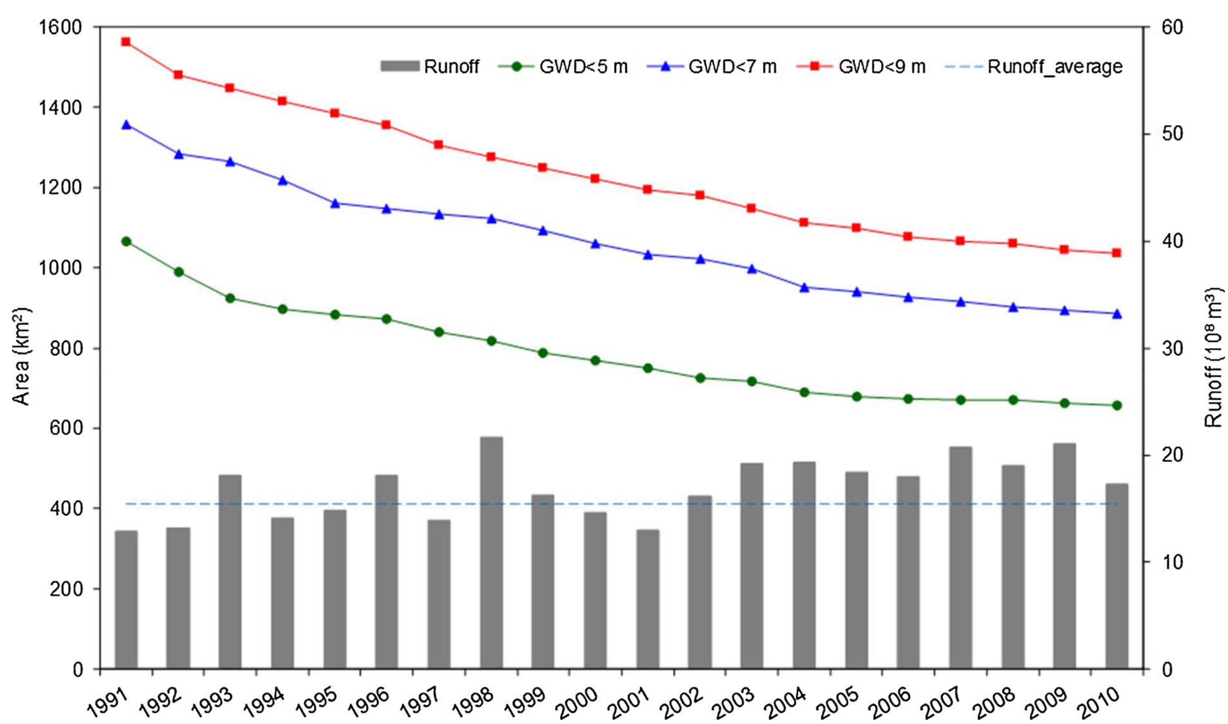

Fig. 10. Changes of area with groundwater depths (GWDs) less than 5 m, 7 m and 9 m, and surface runoff entering the middle oasis through Yingluo gorge during 1991–2010.

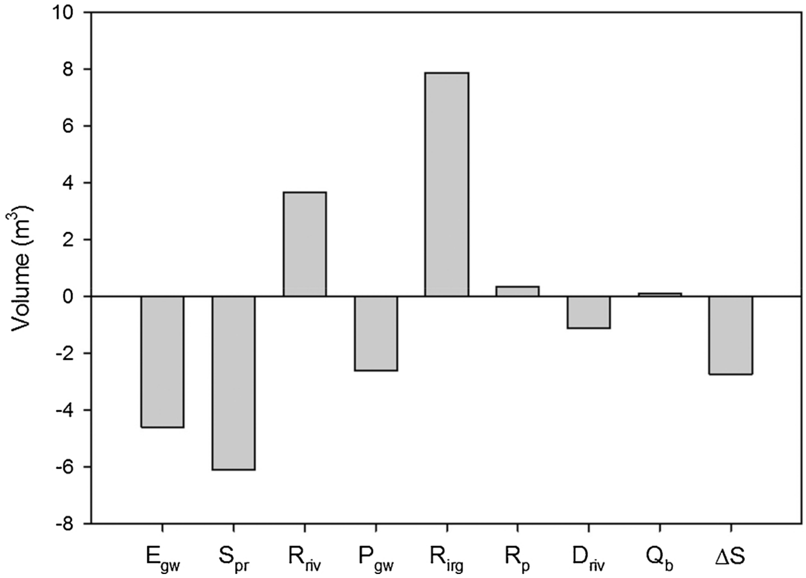

Fig. 11. Simulated average annual values for groundwater budget terms in the Zhangye basin during 1991–2010. E_{gw} is the groundwater evaporation, S_{pr} is the volume of spring overflow, R_{riv} is the groundwater recharge from Heihe River, P_{gw} is the groundwater exploitation, R_{irg} is the recharge from irrigation, R_p is the recharge from precipitation, D_{riv} is the discharge to the Heihe River, Q_b is the lateral boundary flux, and ΔS is the storage change of groundwater system. Positive and negative values refer to the recharge and discharge, respectively.

the discharge components in that period. However, after 1997, less surface water was diverted for irrigation in those districts far from the Heihe River or at the tail of canal system (like zone 1), and more groundwater was pumped as supplement to fit the increasing water demand induced by agricultural expansion. As a result, total groundwater recharge was only half of discharge, causing the decline of GWLs.

On the other hand, there were also some regions in which the ecosystem was relatively safe. Such as, zone 2, located at the head of canal system could divert enough surface river water for irrigation. GWLs only declined in a few years, especially in dry years, and then rose up to a similar level in the following wet years as compared with that.in 1991. Moreover, zone 4 located nearby the Heihe River could also receive abundant surface water for irrigation. Enough or even excessive surface water and the intensive interaction with Heihe River had made the GWL in a relatively stable situation. However, agriculture in those areas should also be limited to a reasonable level, so that other areas could obtain more surface water avoiding over groundwater pumping.

3.5. Insight on irrigation and groundwater management

In this study, modeling results clearly presented several problems of continuous water table decline and the related impact factors in a long-term period. Increase in irrigated area and irrigation water demand

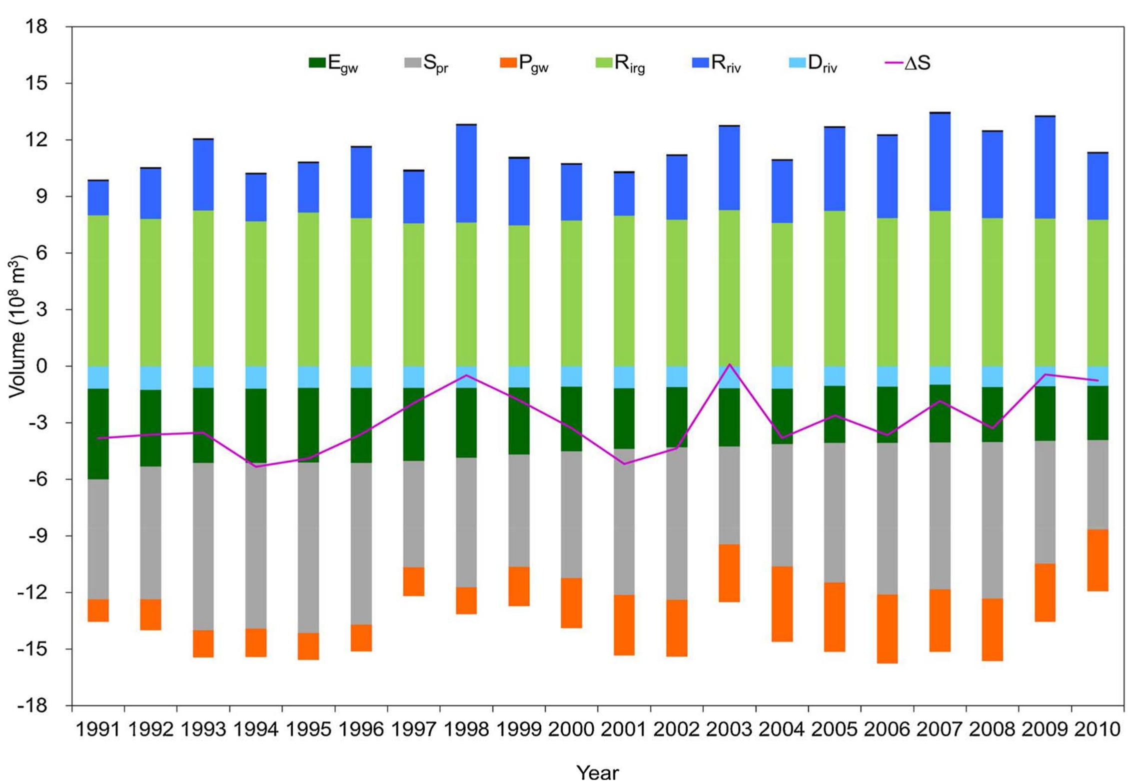

Fig. 12. Simulated annual changes of groundwater balance terms in the Zhangye basin during 1991–2010. E_{gw} is the groundwater evaporation, S_{pr} is the volume of spring overflow, R_{riv} is the recharge from Heihe River, P_{gw} is the groundwater exploitation, D_{riv} is the discharge to the Heihe River, R_{irg} is the recharge from irrigation, and ΔS is the storage change of groundwater system. Positive and negative values refer to the recharge and discharge, respectively.

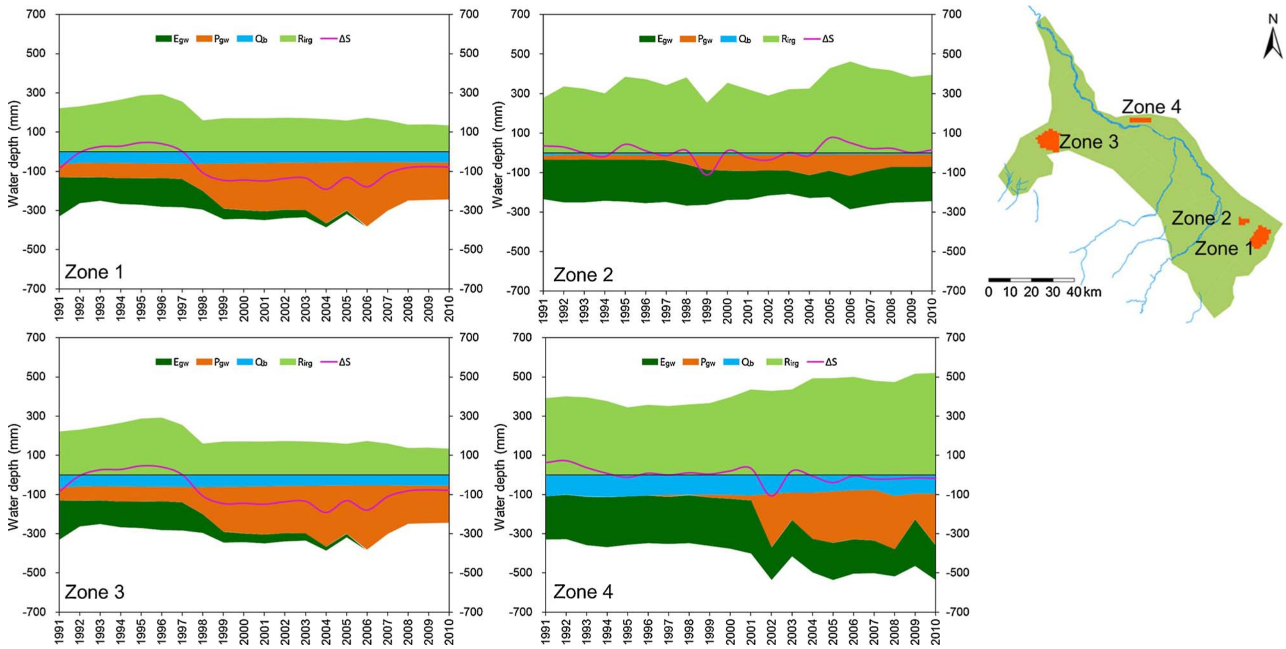

Fig. 13. Modeling results of groundwater budget and annual changes of water balance items for four selected typical zones. E_{gw} is the groundwater evaporation, P_{gw} is the groundwater exploitation, R_{irg} is the recharge from irrigation, Q_b is the lateral boundary flux, and ΔS is the storage change of groundwater system. Positive and negative values refer to the recharge and discharge, respectively.

resulted in significant GWL decline. The reduction of river water allocation after applying EWDP led to larger or excessive groundwater exploitation, due to unreasonable management of groundwater pumping and relatively lower efficiency of water-saving practices that mainly focused on construction of canal system (for economic benefits) but in deficit of well management. The area with GWDs less than critical ones was even reduced by 30%, which was obviously dangerous evidence to the growth of natural vegetation and the health of ecosystem. The recovery of groundwater level in some local areas was mainly caused by wetter climate in 2000s instead of management improvement. The overall declining trend of GWLs was still foreseen if irrigation water, crop pattern and land use were maintained as present. Those would strongly challenge the sustainable development of the Zhangye basin, and require a balance between economic development and ecosystem restoration. Modeling results showed that the appropriate alternatives should have focused on: (1) controlling or even reducing the farmland area, e.g. returning farmlands to grasslands; (2) supervising groundwater pumping and/or close wells in those areas with significant GWL decline, e.g. in downstream basin; (3) implementing the water-saving practices (WSPs) at both farmland and regional scale to improve field water use efficiency, increase conveyance efficiency by means of providing services in practices, and prevent the possible over groundwater pumping in lower reaches of canals and rivers. Strategies to restore eco-environment should also be determined according to the local conditions and classification. Overall, how to recover the groundwater levels was quite necessary to be studied in future. The effects of various alternatives on groundwater dynamics would be further investigated in our follow-up researches.

4. Conclusion

The Zhangye basin of Heihe River basin (HRB) was chosen as the representative case for analyzing the long-term groundwater dynamics affected by the rapid development of irrigated agriculture in arid inland river basins of northwest China. A three-dimensional groundwater flow model was developed for the Zhangye basin of middle oasis of HRB, with carefully considering the recharge from field irrigation determined by using an ago-hydrological model (SWAP-EPIC). The model was well calibrated and validated with the groundwater level (GWL) data of 50 observation wells over the periods of 1991–2001 and 2001–2010, respectively. Then the model was used to analyze the long-term GWL dynamics and water balance changes and to further identify their impact factors.

Firstly, the detailed groundwater dynamics for a long-term period (20 years) were given in this study compared to the former researches. Three GWL trends were found, i.e. relatively stable trend, decreasing and then increasing trend and continuously or even extremely decreasing trend. As a result, the average GWL declined with an average rate of $9\,cm\,a^{-1}$ for the Zhangye basin. Secondly, recharge from irrigation water (R_{irg}) and that from river seepage (R_{riv}) respectively accounted for 64.3% and 31.7% of the total recharge, whereas the spring overflow (S_{pr}), groundwater evaporation (E_{gw}), groundwater pumping (P_{gw}), and discharge to the rivers (D_{riv}) accounted for 42.3%, 31.9%, 17.9% and 7.9% of the total discharge, respectively. The balance of groundwater system for the Zhangye basin was negative with a value of $-2.7 \times 10^8\,m^3$ per year in average. Thirdly, some areas with large groundwater exploitation were suffering from the continuous GWL decline. The average storage change (ΔS) could reach to -100 mm water depth, resulting in obvious groundwater funnel in the basin. Fourthly, the area with critical groundwater depth (e.g. < 5 m) has reduced about 30% in 2010 as compared with that in 1991. Relevant ecosystem restoring measures were also proposed, focusing on controlling or reducing the farmland area and groundwater exploitation, and promoting the water-saving practices. It should also be useful to irrigation water use for oasis areas in other inland river basins that are facing the similar water use issues. The strategies for restoration measures and the related decision making on groundwater management in oasis areas should be further studied in the follow-up researches.

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