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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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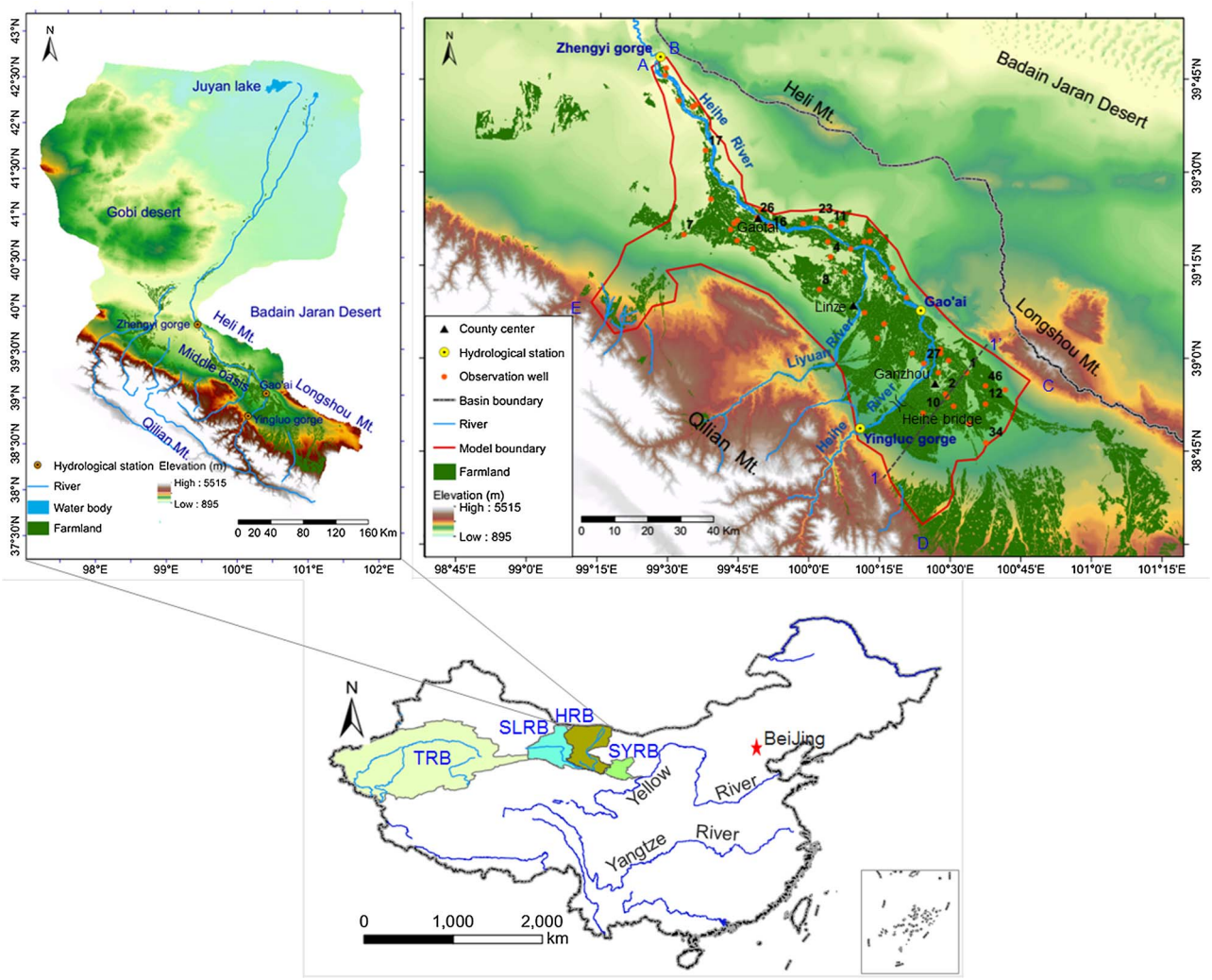

Fig. 1. Location and hydro-geological conditions of the modeling area (Zhangye basin) in the middle Heihe River basin, and distribution of farmlands and groundwater observation wells (the middle reach are defined as the reach between Yingluo gorge and Zhengyi gorge).

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