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Establishing a model of conjunctive regulation of surface water and groundwater in the arid regions

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ABSTRACT

A conjunctive model was established to regulate surface water and groundwater allocations in an arid river basin in northwest China. In the model, water data for the current year was used to calculate the optimal water resources allocation in the basin for a future year. Results showed that the current water resources were sufficient to meet the highest priority water needs (daily life, industry, ecological environment), but there was insufficient water to meet the needs of arable agriculture, including irrigation, in its current form. The model results highlight the need for reduced groundwater exploitation, agricultural planning and protection of the ecological environment.

1. Introduction

The sustainability of water resources is a critical issue against the backdrop of rising water demand for agricultural, industrial, and domestic (FAO., 2013), The issue has become more challenging in the light of shrinking water resources due to urbanization, contamination, and climate change impacts, especially in the arid zones of the northwest of China where water is the key to sustained social and economic development, and is vital for maintaining the ecological environment (Chen et al., 2012; Jia et al., 2012). The ideal condition of having the appropriate amount of good-quality water at the desired place and time is most often not satisfied (Huo et al., 2016). The Shiyang River Basin is deep in the Chinese hinterland. It is one of a number of river basins in this area that suffer a chaotic water situation, and is under regulation (Wei et al., 2005; Wang et al., 2007). Many of the problems that exist in the basin can, to some extent, be attributed to severe water resource shortages and unreasonable water resource allocations, both at a regional level (within-basin shortages between the midstream and downstream reaches), and for industrial use (Shen et al., 2005; Wang et al., 2001).

In arid areas, groundwater is the most critical factor in maintaining the ecological balance (Zhang et al., 2014). If groundwater abstraction exceeds the natural groundwater recharge for extensive areas over long terms, overexploitation or persistent groundwater depletion occurs (Gleeson et al., 2010), leading to the deterioration of the ecosystems and expansion of desertification (Chen et al., 2004). Surface water–groundwater conjunctive regulation currently provides an effective solution for the water resource scarcity issues in arid inland river basins (Tuinhof et al., 2003; Sun et al., 2009; Gao et al., 2004), by using more surface water in the wet season and making appropriate use of groundwater in the dry season. This method takes full account of the mutual compensation function between surface water and groundwater. It also helps to alleviate the contradictions between the supply and demand of water resources, so that regions can cope with increasing water demands and changes in climate variability. All of these factors are important when optimizing the allocation of water resources, which is necessary to ensure sustainable development in arid inland river basins (Yu, 2010; Zhao et al., 2010). During the recent years, simulation-optimization (SO) approaches are widely

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used in water sources management and planning (Singh, 2014a,b; Rodriguez-Sinobas et al., 2016). SO has been implemented to the issue of conjunctive use of surface water and groundwater as well (Wu et al., 2016). In 1961, Buras and Hall introduced the concept of dynamic planning to a surface water and groundwater conjunctive system for the first time (Qi et al., 1999). Maddock (1974) developed a model for determining the operating rules for conjunctive use of surface water and groundwater under the stochastic demand and supply sources. Marino (2001) concluded that the conjunctive use simulation–optimization models could help to analyze impact vulnerability and adaptation to climate change scenarios considering all together surface water and groundwater resources and the interaction between them. Li et al. (2008) used the Hydro-GeoSphere model to analyze the coupling simulation of groundwater and surface water systems in Toronto, Canada. Törnqvist and Jarsjö (2012) used a distributed hydrologic model simulating coupled groundwater-surface water-systems at the basin scale and the results showed that implementation of more efficient irrigation systems would result in much larger water savings in the more arid downstream regions. However, most of the model structure is very complex, and requires many parameters and input data, and there exists the shortage of the computing speed and convergence. Model building and calibration are also very time-consuming, which limits their application (Huo et al., 2016). Therefore, when modelling, we shall consider both reduce the complexity of the model, and make the convergence of the model robustness. In view of large-scale surface water and groundwater systems are complex and difficult to manage, and such conjunctive regulation of water use in Shiyang River Basin is lacking and it is a prerequisite for adapting regional development to changing water supply regime, attributed to both climate change and human activity. The aims of this study were therefore (1) to analyze surface water and groundwater data for the arid inland Shiyang River Basin, using the large system decomposition–coordination method, (2) to optimise the structure of the water supply system in space and time, and (3) to promote reasonable development and efficient use of the limited water resources in this arid river basin.

2. Materials and methods

2.1. Study area

The Shiyang River Basin is located in the Hexi Corridor of Gansu Province, China. It is a typical inland arid basin with a high use of water resources. The basin encompasses an area of 4.16×10^4 km^2 with a population of 2.2 million and covers the area between 101°41′–104°16′E and 36°29′–39°27′N (Fig. 1) and ranges in elevation from 5254 m asl in the headwaters to 1300 m asl the tail of downstream end. The Shiyang River Basin is surrounded by the Badain Jaran Desert in the north, the Tengger Desert in the east, the Qilian Mountain in the south and the Heihe River basin in the west. The annual precipitation is uneven distribution in spatial and temporal, occurred mainly from June to September, and mainly concentrated in the highland of Qilian mountain, with an annual precipitation of 300–600 mm, whereas seldom precipitation in plain arid regions, with an annual precipitation less than 200 mm. In contrast, the potential evaporation ranges from 700 mm in the mountains to more than 2600 mm in the desert plains (Ma et al., 2012). The Shiyang River originates from the Qilian mountains with eight tributaries-from east to west these comprise the Dajin River, Gulang River, Huangyang River, Zamu River, Jinta River, Xiyin River, Dongda River and Xida River, which are mainly fed by rainfall, snowmelt and glacier melt in the Qilian mountains. The average water resource is 16.61×10^8 m^3, of which surface runoff is about 15.61×10^8 m^3 and groundwater is 1.00×10^8 m^3(Li et al., 2016). The middle and lower reaches of the Shiyang River are important agricultural regions despite being arid with low annual precipitation and high potential evapotranspiration. But the planting structure is not reasonable and the agricultural area expanded unreasonable, agricultural water serious exceed the water resources carrying capacity in region. The planting proportion of crops with high water consumption is very high, for instance, Spring wheat is the main irrigated crop in this region, and it consumes most of the irrigated water (Tong et al., 2007). The Shiyang River Basin consists of four sub-basins, which are the Wuwei sub-basin (WWB), the Minqin sub-basin (MQB), the Yongchang sub-basin (YCB) and the Jinchuan sub-basin (JCB). The WWB and YCB are part of the upstream basin, whereas the MQB and the JCB are parts of the downstream basin. Two important reservoirs lie between the upstream and downstream, which are the Jinchuanxia Reservoir (JCXR) between the YCB and JCB and the Hongyashan Reservoir (HYSR) between the WWB and the MQB. Each sub-basin has a relatively independent groundwater flow system (Fig. 1). Reservoirs have been built on each river, except the Zamu River (Hu et al., 2009).

2.2. The conjunctive regulation model of surface water and groundwater

2.2.1. Generalisation of the system

A conceptual model of the present state of the water resources system in the Shiyang River Basin was developed from an analysis and generalisation of the water supply network and the transformations and relationships between the different water resources. The study area is divided into two subsystems-Xidahe system and the Liuhesystem- according to the watershed system, includes seven irrigation areas (e.g. Liuhe irrigation area (LHIA), Xihe irrigation area (XHIA), Siba well irrigation area (SBWIA), Minqin Mixed irrigation area (MQMIA), Changning Mixed irrigation area (CNMIA), Jinchuan Mixed irrigation area (JCMIA) and Wuwei well irrigation area (WWWIA)). There are four reservoirs (e.g. Liuhe reservoir(LHR), Xidahe reservoir(XDHR), Hongyashan reservoir(HYSR) and Jinchuanxia reservoir(JCXR)) and four underground aquifers (e.g. Wuwei, Yongchang, Minqin and Jinchuang-Changning). Base on this information, a map was constructed for the water resources allocation network in the study area (Fig. 2).

2.2.2. Model establishment

A model for harmonious regional development in the river basin was adopted so that the various aspects of the basin's demands could be achieved; this model was used to study the optimal allocation of water resources in the river basin with an overall consideration of issues such as growth, efficiency, and fairness.

2.2.2.1. Objective function. In a water basin where there are water shortages, fair allocation and use of water resources can have a direct influence on the development of a subarea. From the analysis of the water resources system and related issues in the river basin, it was considered that the objective function based on the minimum rate of relative scarcity of water developed by Wang et al. (2006) would be an appropriate tool to relieve the issues of water resource shortages and competitive water use:

$$\min z = \sum_{n=1} \sum_{t=1} \left(\frac{D_{nt} - \sum_{i} S_{int}}{D_{nt}} \right)^2 \tag{1}$$