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Conjunctive use of surface and ground water resources using the ant system optimization

Hamid R. Safavi*, Sajad Enteshari

Department of Civil Engineering, Isfahan University of Technology, Isfahan, Iran

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ABSTRACT

Conjunctive use of surface and ground water resources forms an important part of integrated water resource planning and management in a basin-wide scale. This paper presents a simulation/optimization model based on artificial neural networks (ANNs) and an ant system optimization (AS) for solving the monthly conjunctive supply of irrigation water. The study area is Najafabad Plain located in the semi-arid west central Iran. The water resources in the region are under increasing pressure to meet the growing irrigation water demand despite the dire decline in its surface water resources due to climate changes. The main objective of the conjunctive use model developed in this study is to minimize the water deficit in the three irrigation zones subject to constraints on groundwater levels and cumulative drawdown for each zone. The results indicate that the simulation model is capable of predicting the behavior of the study aquifer and that it may be used as a decision support system. Moreover, both the simulation and the optimization models are found capable of determining water extraction quantities required so that not only will the present water deficit decline but aquifer conditions will improve as well.

1. Introduction

Recent decades have witnessed serious threats to the sustainability of water resources and a formidable drawdown in water tables, especially in semiarid regions, due to over urbanization, increasing irrigation demand, and climate change impacts. Thus, the sustainability of water resources largely depends on proper management and efficient utilization of agricultural water (Amini Fasakhodi et al., 2010). One way to achieve this objective is to adopt such management systems as optimum conjunctive use of surface and ground water resources since the availability of one water resource may not be able to meet the entire irrigation requirements (Nevill, 2009; Harmancioglu et al., 2012; Singh, 2013, 2014a). The advantages of the conjunctive use of surface and ground water resources are not limited to lifting water shortages but it is also capable of enhancing water use efficiency and improving the environmental conditions of irrigated areas (Azaiez, 2002; Cosgrove and Johnson, 2005; Liu et al., 2013; Singh, 2014b). Conjunctive use is generally defined as the allocation of surface and ground water resources to one or several uses on a quantitative and/or qualitative basis while certain constraints are also taken into consideration (Rao et al., 2004). Over the past two decades, different numerical models (e.g., MODFLOW) have been developed to investigate the interactions between surface and ground water systems (Ramireddygari et al., 2000; Reeve et al., 2001). These models can precisely simulate both the spatial and the temporal variables involved. However, they are handicapped by such limitations as the need for skills and expert knowledge to perform simulations and the requirement to collect a large body of data. These limitations have in recent years led to the increasing use of data-driven models such as artificial neural networks (ANNs). ANNs have been successfully used in predicting groundwater level in different areas (Coulibaly and Anctil, 2001; Coppola et al., 2003; Triana et al., 2003; Coppola and Rana, 2005; Daliakopoulos et al., 2005; Lallahem et al., 2005; Nayak et al., 2006; Mohanty et al., 2010; Trichakis et al., 2010). The two methods of "embedding" and "response matrix" have been introduced for the optimal management of ground and surface water resources. The embedding method is inefficient when applied to large aquifer systems with significant numerical heterogeneity and the response matrix method which has been employed in a large number of studies (Lefkoff and Gorelick, 1986; Galeati and Gambolati, 1988; Karatzas and Pinder, 1993; McKinney and Lin, 1994; Keshari and Datta, 1996; Belaineh et al., 1999; Shen et al., 2004; Alimohammadi and Afshar, 2005; Psilovikos, 2006) is only applicable to resources at particular points (Gorelick, 1983).

A review of the literature suggests that the combined simulation and optimization models have been around for quite some time and

* Corresponding author.
E-mail addresses: hasafavi@cc.iut.ac.ir (H.R. Safavi), s.enteshari@cv.iut.ac.ir (S. Enteshari).

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have remained popular as efficient tools for dealing with allocation problems (Ejaz and Peralta, 1995; Ranganathan and Palanisami, 2004; Vedula et al., 2005; Shi et al., 2012; Safavi and Esmikhani, 2013). Safavi et al. (2010) presented a relatively comprehensive classification of the optimization models employed for the conjunctive use of water. Due to the high capability of meta-heuristic optimization techniques for finding globally optimum points, the use of these methods in combination with data-driven simulation models has been on the rise over the last decade. Surrogate-based optimization approaches are promising for computationally expensive models. The core idea in these approaches is to replace the original complex model by a simple and computationally cheap surrogate one in the optimization process (Wu et al., 2016). Wang and Zheng (1998) and Fayad and Peralta (2004) used Genetic Algorithm (GA) successfully in the management of water resources. Karamouz et al. (2005) developed a method to optimize the conjunctive use of surface and ground water resources using ANN and GA with an emphasis on water quality. Yang et al. (2009) considered integration of the genetic algorithm, dynamic programming, and groundwater simulation model to solve a multi-purpose water resource management problem. A trained ANN used as a simulator of surface water and ground water interactions and a genetic algorithm used as the optimization model were developed by Safavi et al. (2010). Safavi and Esmikhani (2013) developed an S/O model for the conjunctive use of surface and ground water by combining Support Vector Machines (SVMs) and genetic algorithms.

The Ant System (AS) is another meta-heuristic algorithm applied to optimization problems. First introduced by Dorigo et al. (1991), the original algorithm has undergone some developments to transform into such new versions as the Ant Colony Optimization (ACO). Abbaspour et al. (2001) introduced one of the first applications of ACO in water resources management for estimating the parameters involved in unsaturated flows. In recent years, ACO algorithms have been used for optimization purposes in water resources management (Ostfeld and Tubaltzev, 2008; Madadgar and Afshar, 2008; Dariane and Moradi, 2009; Ataie-Ashtiani and Ketabchi, 2010).

Some of the decision support systems developed for conjunctive management of ground and surface water resources take advantage of multi-objective optimization models for developing water allocation policies. In these models, the different priorities of both consumers and stakeholders should be taken into account (Safavi et al., 2016).

The present study focuses on the single objective optimization model for the conjunctive use of surface and ground water resources using a trained ANN model as a simulator linked with an AS algorithm for optimization purposes to minimize the water deficit in the three irrigation zones subject to constraints on groundwater drawdown.

A thorough and detailed investigation is carried out of the study area in an attempt to identify the factors that need to be included in a simulation model of the aquifer. In the next stage of the study, a simulation model and an improved optimization one are integrated into a combined model to provide a method for the optimal conjunctive management of the water resources available in the study area. Fig. 1 shows a schematic representation of the method thus developed using a linked ANN-simulation and AS-optimization model.

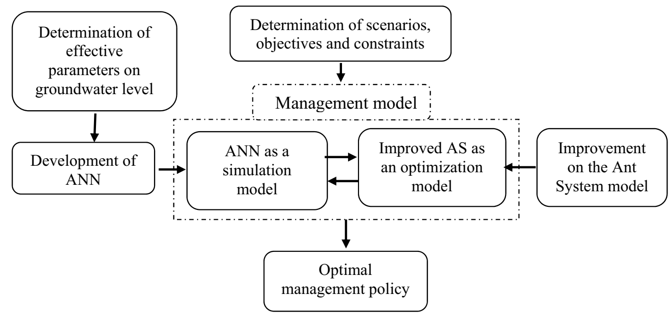

Fig. 1. Schematic representation of the linked simulation-optimization model.

2. Materials and methods

2.1. Study area

The Najafabad Plain is one of the most important sub-basins of the Zayandehrud River basin in central Iran (Fig. 2). Covering an area of 1712 km^2, the area which is trapezoid in shape is located between 32°20′ and 32°49′ N latitudes and 50°57′ and 51°44′ E longitudes along a north-west to south-east direction. The minimum and maximum altitudes of the sub-basin are 1579 and 2924 m above mean sea level, respectively, and the general slope of the basin runs from west to east and northeast.

The Najafabad aquifer has an area of about 1142 km^2 with an average thickness of 60 m, a minimum thickness of 30 m, and a maximum of 120 m. The average hydraulic conductivity in this unconfined aquifer is about 0.8 m/day and the mean value of its specific yield is about 0.05. A total number of about 10,160 pumping wells are operating in the aquifer with discharge rates ranging from 2 to 110 *l/s*. The average water extraction over the past twenty years amounts to 720 million cubic meters (MCM) per year. The aquifer is recharged by irrigation percolation, seepage from the local water channels and the river, and direct precipitation. The annual recharge is estimated to be about 650 MCM, indicating an imbalance between recharge and consumption.

The aquifer offers a high potential for agriculture but, in spite of the modern irrigation networks erected in the region, the underground water resources in the plain are under a great pressure due to overexploitation. This high abstraction has led to a negative water balance and a serious water shortage in the plain.

The most important surface water body in the region is 36 km away from the Zayandehrud River located southwest of the aquifer. The Zayandehrud River runs over a course of about 350 km and its flow in the best wet years amounts to 30 m^3/s to provide not only drinking water for a population of approximately 4.5 million but also to supply water to about 250,000 ha of agricultural lands and industrial establishments that form the second largest industrial zone in Iran. The Nekouabad Left and Right channels transfer water from a diversion dam to the left and right banks of the river and the Khamiran channel transfers water from a storage dam to the western part of the sub-basin during the dry and warm seasons. Since there are three important irrigation networks in the agricultural areas of the plain and also because it is important to determine the groundwater level and the allocation to each area, the study area is divided for the purposes of this study into three zones. Fig. 2 shows the Najafabad aquifer, the stretch of the river that passes through the sub-basin, and the modern irrigation networks. All the data on the extraction wells including their pumping rates, geographical locations, and history of operation were obtained from published report and used to determine groundwater extraction in each zone (Isfahan Regional Water Company, 2013, 2014).

The region is characterized by an average annual precipitation of 174 mm, a mean annual temperature of 14 °C, and an annual potential evaporation of 2340 mm, all of which are characteristic of semi-arid regions. The meteorological data on the study area were derived from the data sheets from the two Tiran and Zefre stations which are evaporation gauges. Located at 32°42′ and 32°30′ N latitudes and 51°09′ and 51°29′ E longitudes, these stations have data records of daily precipitation, evaporation, and temperature since 1970. Monthly groundwater levels were determined using the data