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Review

Simulation–optimization modeling for conjunctive water use management

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A R T I C L E I N F O

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A B S T R A C T

Good quality surface water and groundwater resources are limited furthermore they are shrinking because of the urbanization, contamination, and climate change impacts. In this backdrop, the proper allocation and management of these resources is a critical challenge for satisfying the rising water demands of agricultural sector. Because irrigated agriculture is the largest user of all the developed water resources and consumes over 70% of the abstracted freshwater globally. The computer-based models are useful tools for achieving the optimal allocation of limited water resources for the conjunctive use planning and management in irrigated agriculture. Various simulation and optimization modeling approaches have been used to solve the water allocation problems. Optimization models have been shown to be of great importance when used with simulation models and the combined use of these two approaches gives the best results. The reviews on the combined applications of simulation and optimization modeling for the conjunctive use planning and management of surface water and groundwater resources for sustainable irrigated agriculture are done and presented in this paper. Conclusions are provided based on this review which could be useful for all the stakeholders.

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1. Introduction

The provision of irrigation is essential for achieving food security to the burgeoning global population (Singh, 2012a) which is expected to touch the 9.5 billion mark by 2050 (United Nations, 2012). The conjunctive use of surface water and groundwater resources is necessary because the availability of one source of water may not be sufficient to fulfill the entire irrigation requirements (Nevill, 2009; Harmancioglu et al., 2013). The conjunctive use improves the water use efficiency and regional environment of irrigated areas (Cosgrove and Johnson, 2005; Cheng et al., 2009) by increasing the reliability of supply when a single source of water is inadequate to meet the demand with sustainability (Singh, 2012b; Liu et al., 2013). The increase in agricultural productivity by minimizing the crop stress is the major benefit of conjunctive water use (Fredericks et al., 1998). Wrachien and Fasso (2002) concluded that the properly managed conjunctive use system yield more water at economic rates than separately managed surface water and groundwater systems.

Burt (1964) first introduced the concept of conjunctive water use and suggested that the surface water and groundwater should be considered as two elements of an integrated water system rather than two separate entities. Ruud et al. (2004) and Islam et al. (2011) evaluated the conjunctive use of two water sources in water scarce semiarid regions. Conjunctive use also allows the use of poor quality water for irrigation (Prendergast et al., 1994; Datta and Jong,

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2002; Kaur et al., 2007; Mandare et al., 2008). Oster and Grattan (2002), Malash et al. (2008), and Rasouli et al. (2013) have demonstrated the successful utilization of conjunctive use of poor quality water for crop production. Garcia-Lopez et al. (2009), Karimov et al. (2012), McCallum et al. (2013), and Nikoo et al. (2013) have reported the various aspects of conjunctive use of surface water and groundwater resources.

During the recent years, a large number of simulation and optimization models have been used for the proper planning and management of conjunctive water use in irrigated agriculture (e.g., Matanga and Marino, 1979; Loucks et al., 1981; Hantush and Marino, 1989; Kite and Droogers, 2000; Huang and Loucks, 2000; Mantoglou, 2003; Lu et al., 2012; Rezapour Tabari and Soltani, 2013; Singh, 2013, 2014a,b). Usually the simulation models are used to get the answer of 'what if' and optimization models come back with the question of 'what is the best' under a particular set of conditions. However, it is unlikely to get an appropriate solution with simulation or optimization techniques alone, and thus the combined use of simulation and optimization models is essential (Singh and Panda, 2013; Singh, 2014c). Ahlfeld and Heidari (1994), Wang and Zheng (1998), Cheng et al. (2000), Ayvaz and Karahan (2008), and Gaur et al. (2011) have used simulation–optimization (SO) models for the solution of different real-world problems. This paper presents an overview of the combined applications of simulation–optimization modeling for the conjunctive use planning and management of surface water and groundwater resources for sustainable irrigated agriculture.

The paper is divided into five sections followed by list of references. Section 1 deals with the significance of the study along with its objectives. The development and application of simulation–optimization models for conjunctive water use planning and management are provided in Section 2. The techniques of integrating the simulation and optimization models are provided in Section 3. Section 4 deals with the applications of management models for multi-objective purposes. Conclusions of the study are provided in Section 5.

2. Background

The SO modeling approach has been widely used to solve the water resources problems (Wagner and Gorelick, 1989; Barlow et al., 1996; Das and Datta, 1999; Mantoglou et al., 2004; Katsifarakis and Petala, 2006). The SO approach is attractive because it can account for the complex water allocation problems and identify the best management plan under a particular set of conditions (Yeh, 1992; Wagner, 1995). One of the main advantages of the SO model is that it provides a structured means to evaluate trade-offs between sustained rate of groundwater withdrawals and surface water depletion (Barlow et al., 2003). The first example of combined application of SO model was reported in the literature about four decades ago (Maddock, 1972). Since then, the SO models have been used extensively for the conjunctive use planning of surface water and groundwater resources (e.g., Kashyap and Chandra, 1982; Bredehoeft and Young, 1983; Chavez-Morales et al., 1985; Matsukawa et al., 1992; Bhattacharjya and Datta, 2005; Karamouz et al., 2007; Ramesh and Mahesha, 2008; Bazargan-Lari et al., 2009; Chang et al., 2011).

Within the SO approach, the simulation models account for the physical behavior of surface water and groundwater systems, whereas optimization models account for the conjunctive management aspects of the systems (Basagaoglu and Marino, 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. A decomposition and multilevel approach was used by Haimes and Dreizen (1977) for solving the problems of conjunctive water use of a large-scale complex groundwater system in which the surface water and groundwater sources were conjunctively used to meet the water needs of several water users in a basin. Molz and Bell (1977), O'Mara and Dulay (1984), Jones et al. (1987), Willis and Finney (1988), and Karterakis et al. (2007) have also adopted the similar approach for the management of water resources. A combination of linear programming (LP) optimization model and simulation model was used by Ibanez-Castillo et al. (1997) for planning the operation of an irrigation system. Two reservoirs, two irrigation districts, and water transfer capabilities between reservoirs were considered in the study.

An SO model was utilized by Mohan and Jothiprakash (2003) to develop and evaluate the alternate priority-based policies for operation of surface water and groundwater resources. An LP-based optimization model was first used to get the optimal cropping pattern, then a simulation model was employed to evaluate the conjunctive operation of the system using the optimal cropping. Willis et al. (1989) presented a conjunctive groundwater–surface water planning model for the Yucheng County region of the North China plain for maximizing the net annual farm income under a range of hydrologic conditions. Later, a similar SO approach was adopted by Jonoski et al. (1997), Psilovikos (1999), and Garg and Ali (2000). Basagaoglu et al. (1999) formulated a non-linear conjunctive use SO model for the objective cost minimization. The non-linearity in the model was eliminated through the delta-form approximation. A dynamic programming SO model was developed by Karamouz et al. (2004) with the aim of meeting the agricultural water demands by reducing the pumping costs and controlling groundwater level fluctuations in the Tehran metropolitan area. The model was used to determine the long-term impacts of different scenarios on conjunctive use policies and watertable fluctuations.

Marino (2001) concluded that the conjunctive use SO models can help to analyze impact vulnerability and adaptation to climate change scenarios considering all together surface water and groundwater resources and the interaction between them. Smout et al. (2006) has demonstrated the potential of an SO approach in which optimal allocation of land and water resources under different allocation units of an irrigation scheme was done. They applied the model in a case study area of Nazare medium irrigation scheme in India. A similar approach was also adopted by Smout and Gorantiwar (2006), Kentel and Aral (2007), and Peralta et al. (2011). Singh and Panda (2013) evolved a unique and simple technique in which they first developed an LP model for optimal allocation of resources. A finite-difference two-dimensional simulation model was then used to assess the long-term impacts of various water management strategies with the optimal land and water use parameters, obtained through the optimization model.

Peralta et al. (1988) used an SO model for planning the optimal spatial distribution of crops to be reliably irrigated by conjunctive use of water resources using stochastic procedure. An SO model was developed by Reichard (1995) for the management of surface water and groundwater resources in southern California. The groundwater flow system was considered as a two-layer system and the available surface water was treated as a stochastic process. An integrated hydrologic-economic modeling framework was presented by Pulido-Velaquez et al. (2006) for optimizing the conjunctive use of surface water and groundwater resources at a river basin scale in Spain. Rastogi (1989), Tracy (1998), and Theodossiou (2004) have employed the similar approach for the water resources allocation and planning. Recently, Safavi and Esmikhani (2013) applied an SO model for the conjunctive use of surface water and groundwater resources in the Zayandehrood river basin of west central Iran. Maximum/minimum cumulative groundwater

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