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Optimizing regional irrigation water use by integrating a two-level optimization model and an agro-hydrological model

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ABSTRACT

Water scarcity has been a crucial issue for sustainable irrigated agriculture in the arid regions. In these regions where conserving water is paramount, optimal allocation and utilization of irrigation water is particularly important. In this study, a process-based regional economic optimization (PBREOP) model was developed for maximizing irrigation water use efficiency and economic benefit of an irrigation system. The PBREOP model is a two-level optimization model with combined use of an agro-hydrological model (SWAP-EPIC). The first level (farm scale) dealt with the optimal distribution of irrigation water and cropping pattern considering various crops and soils in a subsystem, using a non-linear programing technique. The second level (district scale) sought out the optimal strategy for irrigation water allocation among different subsystems using a dynamic programing algorithm. The crop water production functions (CWPFs) were an important component of the first-level objective function. They were derived with the SWAP-EPIC model considering different irrigation alternatives. The model was solved using the decomposition-harmonization method for large systems. The Yingke Irrigation District (YID) in the middle Heihe River basin, Northwest China was used as a case to test the PBREOP model. Nine CWPFs for three major crops and three major soils were firstly derived based on the simulations of different irrigation levels and climate conditions (20 years). Next, the PBREOP model for YID was established with 11 subsystems, and applied to the irrigation water use optimization under five water supply scenarios. Results showed that the total economic benefit in YID could be increased by 15% on average through the optimization of water allocation and cropping pattern with the same water supply amount as that of the current situation. A variation range of the risk was also obtained with considering the impacts of climate uncertainties. Scenario analysis showed that the total irrigation water could be reduced by 23% on average without benefit reduction when compared to the benefit of the present situation. Model test indicated that the proposed PBREOP model can efficiently optimize irrigation water use and cropping pattern on a regional scale.

1. Introduction

Water scarcity has been a major constraint to social-economic development around the world in the last few decades. The problem will be likely exacerbated due to the rapid increase in population, a dryer climate, and expansion of water demands (IPCC, 2007). Food demand continues to rise with increasing population. According to the FAO analysis of 93 developing countries (Bruinsma, 2003), most of the increases in agricultural production will be in irrigation systems. Worldwide, the irrigated agriculture as the largest water user is subjected to water allocation cuts due to the rapid growth of water demand for non-agricultural sectors (e.g. domestic, industrial, recreational, ecological and environmental use) in both developed and developing counties (Playán and Mateos, 2006; Levidow et al., 2014). Moreover, inefficient usage of irrigation water, particularly in many irrigated areas, has caused significant problems of non-uniformity of irrigation water, man-induced salinization and desertification, and water quality degradation (Pereira et al., 2002; Singh and Panda, 2013; Levidow et al., 2014). Water saving will be an urgent issue for the irrigated agriculture sector.

It is noted that the economic return from improvement of management practices is often orders of magnitude larger than that from improvement of structures (Playán and Mateos, 2006;

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Levidow et al., 2014). Nevertheless, regional decision makers prefer to look at water structure improvements for water saving, due to reasons of compromise, and because it can stimulate other economic sectors. At present, inappropriate planning and management in irrigation districts is still one of the main reasons for excessive irrigation and water waste, particularly in many developing countries (Levidow et al., 2014; Playán and Mateos, 2006; Jiang et al., 2015). In many irrigation districts throughout the world, there is still a great potential to save water through the optimization of irrigation and land management, besides irrigation structure construction and improvement.

Two approaches are commonly used to develop efficient alternatives for improving water use in irrigation districts; these are based on agro-hydrological process simulation models and optimization models. The simulation models can quantitatively describe complex interactions among plant, soil, water, atmosphere and groundwater. After proper calibration and validation, these models can be adopted to do scenario analysis for searching preferable management strategies. In the last two decades, many models (e.g. SWAP, SWAT, DRAINMOD and SimDualKc) have been widely used for improving irrigation schedules and methods as well as drainage system design (Singh et al., 2006a; Pereira et al., 2009; Ma et al., 2011; Sun and Ren, 2014). Most studies are focused on the field scale, and some are also extended in recent years to the regional scale through integration of remote sensing (RS) and geographic information system (GIS) techniques (Singh et al., 2006b; Xu et al., 2011; Jiang et al., 2015). However, using the simulation model only would solve the question of "what if" (Singh, 2014), which means the management strategy decisions are based on scenario analysis of several pre-specified alternatives. Thus, the obtained solution was generally a better one as compared with other defined scenarios but not the optimal one, particularly for regional problems. In previous studies, some researchers have attempted to involve optimization algorithms to overcome the shortcomings of the simulation models for irrigation management optimization (Singh, 2012; Singh and Panda, 2013). The simulation models can be internally or externally linked with the optimization approaches for field scale issues (Shang and Mao, 2006; García-Vila and Fereres, 2012; Darshana et al., 2012). On a regional scale, the combined use of simulation and optimization models appears more often in groundwater modeling with loosing linkage (Rejani et al., 2009; Safavi et al., 2010). To our knowledge, there are few reported cases of optimizing regional irrigation water use with an agro-hydrological simulation model. This may primarily because that the spatial variations of land and water resources aggravate the non-linearity and complexity of the agro-hydrological process simulation (Ines et al., 2006).

On the other hand, the optimization models have been extensively applied in irrigation planning and management as part of a strategy to find the optimal utilization of limited water and land resources (Singh, 2012). Its application involves the optimization of irrigation scheduling, water allocation, water conveyance operation, and cropping pattern, etc. Various optimization techniques, such as traditional methods of linear programing (LP), non-linear programing (NLP) and dynamic programming (DP), and the artificial intelligence search methods such as genetic algorithms (GA) and simulated annealing (SA), have been widely used to find the optimal solution of the target problem through solving the objective functions subjected to some constrains (Singh and Panda, 2012; Haq et al., 2008). Furthermore, the optimization methods with uncertainties (e.g. stochastic programming, fuzzy-parameter programming and interval-parameter programming etc.) are also employed in conventional optimization models for considering uncertainty and randomness in optimization parameters (Ganji et al., 2006; Zhang and Li, 2014; Li et al., 2013; Li and Guo, 2015). In addition, the large system optimization theory that uses a multilevel hierarchical structure has become an effective method to solve complex regional optimization problems (Paul et al., 2000; Shangguan et al., 2002). This theory has an advantage of breaking down complex problems into multilevel optimization problems which can be solved individually using simple optimization methods.

However, for most irrigation optimization methods, the economic objective functions are based on a set of empiric functions describing mathematical relationships between variables, typically the crop water production functions (CWPFs). For example, the CWPFs of the models proposed by Jensen (1968) or FAO (Doorenbos and Kassam, 1979) are usually integrated with water balance equation to form the basis of economic objective functions. These have been successfully used in irrigation optimization both on field and regional scales (Alvarez et al., 2004; Garg and Dadhich, 2014). CWPFs are generally expressed as a simple polynomial function that describes the crop production (yield or dry matter) response to water use (evapotranspiration or crop transpiration) or water applied in the field (irrigation or irrigation plus rainfall). CWPFs were traditionally obtained from long-term field experiment, and this is expensive and time-consuming. In addition, the CWPFs are site-specific and also vary in different climatic years, especially when yield is expressed as a function of applied irrigation water (Saseendran et al., 2015). Most uncertainty methods directly consider the uncertainty and randomness of meteorological factors (mainly rainfall) in the objective functions. Nevertheless, the uncertainty of CWPFs itself resulting from the changes of environment was rarely involved. Using the calibrated simulation model to determine the CWPFs has the advantages of time and effort saving, especially for regional problems (Saseendran et al., 2015). It is also convenient to consider the climate uncertainties for CWPFs. In addition, the dynamic processes (e.g. changes in capillary rise and percolation) can be well described using the process simulation model.

In summary, the method of integrating the optimization and process simulation models is preferred recently, but is still rarely applied for regional land and irrigation water management, mainly due to the complexity of agro-hydrological processes (Singh, 2012). It would therefore be attractive to find a practical and convenient way to integrate the simulation model and the optimization model for searching optimal irrigation management strategy on a district scale.

The objective of this study is to develop a process-based regional economic optimization (PBREOP) model by integrating a two-level optimization model and an agro-hydrological model (SWAP-EPIC) (Xu et al., 2013). The two-level optimization model could be solved by using the decomposition-harmonization method of large system (Shangguan et al., 2002). The SWAP-EPIC model was adopted to derive CWPFs with considering climate uncertainties, and these CWPFs were used as the important component of the first-level objective functions of the PBREOP model. The PBREOP model aimed at determining the optimal irrigation water allocation and cropping pattern to achieve overall maximum economic benefit under limited water resources on a regional scale. This model was then tested in a case study in the Yingke Irrigation District (YID) in the middle Heihe River basin, Northwest China, in order to find the optimal use of multiple irrigation water (surface water and groundwater) and optimal cropping pattern under different water supply scenarios.

2. Methodology

2.1. System consideration

When formulating the PBREOP model, the whole irrigation district was regarded as a system that could be irrigated with surface