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Optimization of irrigation scheduling for spring wheat based on simulation-optimization model under uncertainty

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ABSTRACT

Water scarcity is the major constraint to social-economic development in arid and semiarid regions, where irrigation needs to be scheduled properly for the main crops. In this study, a simulation-optimization model for crop optimal irrigation scheduling under uncertainty was developed to maximize the net benefit. The model integrated a water-driven crop model (AquaCrop) with the optimization model, and incorporated the generation technique for the interval values of hydrological parameters (i.e., precipitation and evapotranspiration) and crop market prices to deal with uncertainties in these variables. The water price was assumed constant. The model was calibrated based on field experimental data obtained in 2014 and validated using 2015 data. The field experiments involved spring wheat (Yongliang No. 4) at Shiyang River Basin Experiment Station in Wuwei City, Gansu Province of Northwest China. The model was then used to generate the optimal irrigation schedules under various irrigation amounts, irrigation events, initial soil water storage and crop market price under uncertainty. Results indicated that the model is applicable for reflecting the complexities of simulation-optimization under uncertainties for spring wheat irrigation water scheduling. The optimization results indicated that the optimal irrigation amount range was [185, 322] mm with the corresponding optimal net benefit of [1.05, 2.77] $\times 10^4$ Yuan/hm^2 and yield of [7.4, 7.6] kg/hm^2 for extreme wet conditions in the basin (defined as the combination of the 5% frequency precipitation with 95% frequency evapotranspiration). For extreme dry conditions, the optimal irrigation amount range was [442, 507] mm with the optimal net benefit of [0.85, 2.64] $\times 10^4$ Yuan/hm^2 and the corresponding yield of [6.6, 7.4] kg/hm^2. Results also showed that four irrigation events under higher initial soil water storage were more likely to produce the higher net benefit and the optimal net benefit would increase as the crop market price increases, as expected. This work can be used to guide irrigation management for local farmers.

1. Introduction

China, a big agricultural country, faces a great challenge of severe water scarcity (Wang et al., 2015). In China, more than 60% of water is used for agricultural purposes; so agricultural water consumption plays an important role in the overall water balance of the country (Wang et al., 2010; Deng et al., 2015). In the northern part of China, water shortage is very serious, because this region has half of the total area of China but less than 20% of total national available water resources (Deng et al., 2006). Especially in northwestern regions, natural rainfall cannot match crop water requirements and supplementary irrigation is needed to sustain and possibly increase crop yields (Zhou, 1996, 2001; Deng et al., 2006).

However, the water available for irrigation has been decreasing in recent years, partly as a consequence of climate change but also due to the increasing competition for water demand from other sectors of the economy, especially industry and domestic consumption (Singh, 2012; Wang et al., 2017). Therefore, it is important that the scarce water resources used in irrigation are optimally allocated in order to guarantee food security, improve farmers' income and improve the general socio-economic well-being in the region.

The basic requirement work for irrigation water allocation in regional scales is to guarantee the crop yield with the limited irrigation water at farm or plot scale. In doing this, irrigation should be accurately

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timed and quantified, i.e., there must be a robust irrigation scheduling program that ensures non-productive soil water evapotranspiration or drainage losses are minimized (Arora and Gajri, 1998). Thus, optimization of irrigation scheduling is basically for optimization of irrigation water allocation. This is essential to ensure water saving and by extension high net benefit for local farmers.

Achieving the optimization of irrigation water scheduling would require knowledge about the response of crop growth/yield to soil water situation, and a model of the economic returns of crop production. In the current study, the former used one of the numerous available crop simulation models and the latter is a bespoke economic model depicting the net benefits for the project.

Crop models were developed in the last few decades for simulating the indices of dynamic crop growth under different irrigation schedules (Bouman et al., 1996). Water-driven models, one type of crop growth models, are based on crop growth controlled by phonological development processes, and they normally assume that crop growth rate is linearly proportional to transpiration through a constant of proportionality (Steduto and Albrizio, 2005). Water-driven models are the least complex and most parsimonious as compared to other crop growth models (Steduto et al., 2007, 2009). It is particularly suitable for semi-arid and arid regions where water is the key limiting factor for crop production. One of the most popular water-driven crop models is AquaCrop (Steduto et al., 2009), which was developed by the Food and Agricultural Organization (FAO) of the United Nations. In recent years, AquaCrop has been widely used to simulate the crop water consumption and crop yield under different irrigation schedules (Salemi et al., 2011; Kiptum et al., 2013; Lorite et al., 2013; Nazari et al., 2013; Vanuytrecht et al., 2014; Kim and Kaluarachchi, 2015; Paredes et al., 2015; Voloudakis et al., 2015; Li et al., 2016a,b,c).

Although simulation models for crop growth are good at describing the effects of various irrigation schedules on the crop growth, they could only be used to get the answers to “what if” questions (Singh, 2014b). It means that the irrigation schedules are based on scenario analysis of several user-defined alternatives. In this case, a number of pre-specified irrigation schedules will be evaluated by comparing the results of crop yield and/or water use efficiency simulated by crop growth models. Then, the irrigation schedule with higher crop yield or net benefit will be recommended. However, whilst the recommended irrigation scheduling may be the best one among the chosen options, it is unlikely to be exactly the global optimal irrigation schedule (Shang and Mao, 2006a,b). To achieve a truly global optimum, optimization methods must be combined with simulation models to derive optimal irrigation schedules (Singh and Panda, 2013; Singh, 2014a).

Genetic algorithm (GA) introduced in the 1970s (Holland, 1975), is one of the frequently used algorithms for solving optimization problems in water management. GA is based on the analogy of the mechanics of biological genetics and imitate the phenomenon of selection of the fittest individuals (Baron, 1998). The solution set in GA is represented by a population of strings, which comprises a number of blocks. Each block represents the individual decision variables of the optimization problem. Strings are processed and combined according to their fitness in order to generate new strings that have the best features of two parent strings. Selection, crossover, and mutation are the three fundamental operations involved in GA to manipulate strings and move to a new generation. Compared with other traditional methods (linear method, nonlinear method and dynamic programming), GA is more likely to be used in solving the simulation-optimization model and it has been widely used in irrigation scheduling optimization or irrigation water allocation (Wu et al., 2007; Moghaddasi et al., 2010; Wen et al., 2017).

In previous simulation-optimization models, the simulation part was usually an integration of crop water production functions (Jensen, 1968) and water balance equation. For example, Shang and Mao (2006a,b) developed a simulation-optimization model based on crop water production functions and produced the optimal irrigation date series for winter wheat in North China. Yu and Shang (2016) determined the optimal irrigation scheduling on a crop rotation system with a multi-objective simulation-optimization model by integrating water balance model, crop water production functions and optimization model. Wen et al. (2017) analyzed the optimal irrigation schedules for spring wheat under plastic mulching using a simulation-optimization model by coupling water balance model, crop water production functions and optimization model. However, crop water production functions were traditionally obtained from long-term field experiments, which are site-specific, expensive and time-consuming. The resulting outcomes of such empiricisms are therefore unlikely to be sufficiently generic as to be transferable to other settings, thus limiting their usefulness. To our best knowledge, there are few irrigation scheduling simulation-optimization modelling schemes, that have coupled crop growth simulation model and optimization model. This is mainly because most of the crop growth simulation models are complex and not convenient to be readily coupled with the other models. Our current work is therefore an effort at closing this knowledge gap.

Another relevant issue to consider is that irrigation scheduling optimizations in real field conditions are more challenging because many uncertain factors are involved, such as climate parameters and economic parameters (Li and Guo, 2014; Li et al., 2016a,b,c). These climate parameters usually change temporally and are complicated by various uncertainties. Such uncertainties will compound the complexity of irrigation scheduling optimization by simulation-optimization models or other traditional methods (Li et al., 2016a,b,c). Most of the previous simulation-optimization models used the average values for the uncertain factors, which would neglect their randomness. Accordingly, introducing uncertainty theory into traditional simulation-optimization method can help to tackle the uncertainty in various input factors, thus reflecting the true complexity and reality of irrigation systems.

Among the widely used uncertainty methods, the interval mathematical programming approach is popular because of its computational efficiency (Li et al., 2018). It considers the uncertainty by approximating the lower and upper boundaries of the variables concerned. In addition, as the major driving factors, hydrological elements, such as precipitation and evapotranspiration usually exhibit various degrees of stochasticity in their behavior that must be accommodated. Therefore it is more thorough for the simulation-optimization based irrigation scheduling to consider the stochasticity occurring in these inputs by fully specifying their complete probability distribution function, whence derive the uncertainty characterization of the optimization decision variables and objective function evaluation.

Wheat, one of the most important food crops, is the staple food for about 34%–40% of the world’s population and 50% of Chinese population (Jia, 2013). China is the largest wheat-producing country in the world. In China the perennial wheat planting area accounts for 25% of the total food crops planting area (Yang, 2010). In the arid regions of northwest China, spring wheat is also widely cultivated with irrigation, as expected (Tong et al., 2007; Jiang et al., 2012). Wheat has a high seasonal water requirement for maximum yields. Border irrigation, sprinkler irrigation and drip irrigation are the main types of irrigation systems. Although drip irrigation and sprinkler irrigation are more efficient than border irrigation (Deng et al., 2006), farmers in arid regions of China prefer to adopt border irrigation because of the low cost of irrigation equipment (He et al., 2013). Thus, spring wheat and border irrigation were selected as the target crop type and the irrigation technology, respectively, for the purpose of investigating irrigation scheduling optimization in this study.

Taking into account the considerations above, the aim of this study is to develop a simulation-optimization model for wheat crop irrigation scheduling that maximizes farmers’ net benefit, given uncertainties in both the climatological and economic situations. The model will integrate a simulation model for crop growth (AquaCrop) and the optimization model formulated to maximize the net economic benefit from