Agricultural Water Management 186 (2017) 86–97

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

An interval multistage water allocation model for crop different growth stages under inputs uncertainty

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ARTICLE INFO

Article history:
Received 7 May 2016
Received in revised form 28 February 2017
Accepted 2 March 2017

Keywords:
Crop growth stage
Interval programming
Irrigation water allocation
Multistage stochastic programming
Water production function
Inputs uncertainty

ABSTRACT

Due to different responses of crop growth stages to the water deficit, it is necessary to optimize water allocation between different growth stages to obtain the maximum food production in reservoir irrigation systems which are widely distributed throughout Southern China and India. In order to address the inputs uncertainties and dynamics existing in the above agricultural water management, an interval multistage water allocation model is developed. By incorporating multistage stochastic programming and interval parameter programming, the developed model can deal with uncertain inputs both expressed as interval parameters and probability distributions, and realize a dynamic irrigation among different growth stages from a reservoir. In the model, water requirement targets are first treated as first-stage decision variables to tackle the unique problem of agricultural water management. Additionally, given that net benefit and penalty of each growth stage are key parameters due to their determinative roles for allocation between different growth stages, a crop water production function is introduced into the calculation to make them factually reflect the competition among different growth stages. The model is then applied to the Yangshudang Irrigation District to plan rice irrigation and demonstrate its applicability. Rainfall has been divided into five levels with probability distributions in each growth stage and parameters have been characterized as interval numbers to show system uncertainty. Five scenarios that represent different initial active storage levels of the reservoir are set to acquire more detailed results. Through the parameter estimation, net benefits are [1.08, 1.29], [5.04, 6.01], [11.79, 14.08] and [1.61, 1.92] RMB/m^3, and penalties are [2.39, 2.48], [11.13, 11.54], [26.05, 27.01] and [3.55, 3.68] RMB/m^3 for tillering stage, booting stage, heading stage and milky stage respectively. Through the model simulation, water requirement targets in booting stage and heading stage under all scenarios are set at their upper bound, while this figure in tillering stage reaches its upper bound only when initial active storage is under high or very high level. The results show that irrigation water can be optimally allocated between different growth stages of a single crop in a single reservoir system under inputs uncertainty. Although there is a limitation to regard rainfall as to be uniform in the whole area, the solutions of water requirement targets under different scenarios, as well as water allocation patterns among different growth stages, are valuable for optimizing irrigation water use in meso- and micro-scale agricultural system under inputs uncertainty.

1. Introduction

In order to meet the nutritional needs of the burgeoning global population which is anticipated to reach 9.3 billion by 2050 from 7.1 billion in 2010 (United Nations, 2010), agricultural production must be increased. However, amidst rapid social and economic growth, water for agricultural irrigation is becoming scarce due to increased competition for water from other sectors, including for domestic, industrial, ecological and hydropower purposes. For example, in China water used in agriculture accounted for approximately 97% of total use in 1949, and this percentage decreased to 88% in 1980, and 69% in 1999, 63% in 2013 and is expected to further decrease to 60% by 2030 (Wu et al., 2003). Therefore, it is important to optimize the management of agricultural water resources to achieve maximum food production (Tan et al., 2014).

Various deterministic optimization models have been employed for agriculture water management and planning (Singh, 2014). For example, many linear, non-linear and dynamic programming optimization models have been used to arrive at optimal irrigation scheduling and multi-cropping pattern (Das et al., 2015; Reca et al., 2001a, b; Kaviani et al., 2015; Rao et al., 1988; Shangguan et al., 2002; Shang and Mao, 2006; Sarker and Ray, 2009), to find the

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http://dx.doi.org/10.1016/j.agwat.2017.03.001
0378-3774/

optimal operating policy of reservoirs or canals (Ahmed and Sarma, 2005; Oliveira and Loucks, 1997; Shyam et al., 1994; Suryavanshi and Reddy, 1986), and to optimize conjunctive use of surface and groundwater (Montazar et al., 2010; Philbrick and Kitanidis, 1998; Rao et al., 2004; Safavi and Esmikhani, 2013; Yang et al., 2009). Besides, in order to achieve more food production, some models that coupled reservoir operation or conjunctive-use operation with irrigation scheduling were proposed for irrigation management (An-Vo et al., 2015; Karamouz et al., 2010; Moradi-Jalal et al., 2007; Sethi et al., 2002; Singh and Panda, 2012; Vedula and Mujumdar, 1992; Vedula et al., 2005). However, the above deterministic optimization models had difficulties in handling various uncertain inputs existing in the agricultural water management problems, such as water inflow, water requirement targets and crop prices.

In order to tackle the above inputs uncertainties, a number of fuzzy mathematical programming, interval parameter programming, and stochastic mathematical programming methods were proposed for agricultural water management (Alaya et al., 2003; Du et al., 2012; Fu et al., 2014; Huang et al., 2012a,b; Li et al., 2011; Lu et al., 2012; Kaviani et al., 2015; Mujumdar and Ramesh, 1997; Rao et al., 1992; Srivastava and Singh, 2015; Stedinger et al., 1984; Vedula and Kumar, 1996; Yang et al., 2005; Zeng et al., 2010). Among these methods, interval stochastic programming is effective for solving problems where the related input data are uncertain but could be expressed as interval values or probability distributions. For example, Li et al. (2010) developed an inexact two-stage water management model for multi-crop irrigation in a large-scale area. Dai and Li (2013) formulated a multistage irrigation model to deal with inter-seasonal water allocation policies. Li et al. (2014) employed an inexact multi-stage stochastic optimization model for solving medium-term agricultural water planning problems.

In most previous studies, interval stochastic programming models only solved optimal water allocation between different crops under inputs uncertainty without considering allocation among different growth stages. However, crop water requirements do not correlate with water inflow. The amount of water inflow may be very low in some growth stages when a great deal of water is demanded, while there may be excessive water inflow in other growth stages that require less water. The same amount of water in different growth stages may bring about differences in crop yield, and the effect of water shortage on crop yield may also change with growth stage. Water allocation among different growth stages should therefore be considered. Additionally, in most previous models, the irrigation targets of crops were treated as first-stage decision variables, which is inappropriate because irrigation targets are closely related to rainfall and cannot be simplistically represented as definite values or interval values. Moreover, few methods have been proposed to appropriately calculate net benefits and penalties which are important input parameters in the interval stochastic programming model.

This study aims to formulate an interval multistage water allocation (IMWA) model to plan agricultural irrigation to maximize system net benefit in a reservoir irrigation system. By incorporating multistage stochastic programming and interval parameter programming, the IMWA model can optimize water allocation between different growth stages under inputs uncertainty including water inflow and water requirements of each stage, crop yield and crop price. In the model, water requirement targets in each growth stage rather than irrigation targets are treated as first-stage decision variables. The water production function is first introduced into the model to calculate the net benefits and penalties of different growth stages. The IMWA model is applied to the Yangshudang Irrigation District to plan rice irrigation to demonstrate its applicability. This water allocation problem has been discussed under five different initial conditions. The optimal solutions obtained can help authorities to develop an appropriate allocation plan for different growth stages of rice under inputs uncertainty.

2. Methodology

2.1. Interval multistage water allocation model

For the sake of improving the utilization efficiency of agricultural water resources, it is necessary to optimize water allocation between different growth stages (Protopapas and Georgakakos, 1990). However, water allocation among different growth stages of crops is a complicated dynamic process because the water inflow and water requirements of each stage are uncertain. In order to solve this problem, an interval multistage water allocation (IMWA) model is presented to plan mono-crop irrigation in a reservoir irrigation system. Considering that irrigation targets are closely related to rainfall and cannot be simplistically represented as interval values, the water requirement targets of each growth stage are treated as first-stage decision variables in the objective function. In terms of constraints, a reservoir water balance equation is introduced to describe the characteristic of the reservoir irrigation system. By incorporating multistage stochastic programming and interval parameter programming, inputs uncertainties expressed as interval parameters and probability distributions can both be reflected, and a dynamic irrigation for each growth stage can be realized. The model can be written as follows:

$$\max f^{\pm} = \sum_{t=1}^{T} B_t^{\pm} WD_t^{\pm} - \sum_{t=1}^{T}\sum_{k=1}^{K_t} P_{tk} C_t^{\pm} WS_{tk}^{\pm} \tag{1a}$$

Subject to

$$WD_t^{\pm} - WS_{tk}^{\pm} \geq W_t^{\pm}, \quad \forall t, k \tag{1b}$$

$$SR_{t+1}^{\pm} = SR_t^{\pm} + WR_{tk}^{\pm} - WI_{tk}^{\pm} - WL_t^{\pm}, \quad \forall t, k \tag{1c}$$

$$WI_{tk}^{\pm} = \begin{vmatrix} (WD_t^{\pm} - WS_{tk}^{\pm} - p'^{\pm}_{tk})/\eta; & WD_t^{\pm} - WS_{tk}^{\pm} \geq p'^{\pm}_{tk} \\ 0; \text{ others} & \end{vmatrix}, \forall t, k \tag{1d}$$

$$0 \leq SR_t^{\pm} \leq SR_{\max} \tag{1e}$$

$$0 \leq WS_{tk}^{\pm} \tag{1f}$$

In which "−" and "+" superscripts represent lower and upper bounds of an interval-parameter/variable, respectively; $f^{\pm}$ = expected net system benefit (RMB), RMB is the legal currency of China; t = index for time period, T = total number of growth stages of crop; $B_t^{\pm}$ = net benefit in period t per unit of water requirement (RMB/m^3); $WD_t^{\pm}$ = crop water requirement target in period t (m^3); k = index for rainfall scenario, K_t = total number of scenarios in period t; P_{tk} = the probability of occurrence for rainfall scenario k in period t, with $P_{tk} > 0$ and $\sum_{k=1}^{K_t} P_{tk} = 1$; $C_t^{\pm}$ = reduction of net benefit (penalty) per unit of water requirement not delivered (RMB/m^3); $WS_{tk}^{\pm}$ = crop water deficit under scenario k in period t (m^3); $W_t^{\pm}$ = crop minimum water requirement in period t (m^3); $SR_t^{\pm}$ = active storage of the reservoir at the beginning of period t (m^3); $WR_{tk}^{\pm}$ = reservoir inflow under scenario k in period t (m^3); $WI_{tk}^{\pm}$ = crop irrigation water under scenario k in period t (m^3); $WL_t^{\pm}$ = water loss of the reservoir during period t (m^3); $p'^{\pm}_{tk}$ = effective rainfall in crop planting region under scenario k in period t (m^3); η = irrigation water efficiency; $SR_{\max}$ = active storage capacity of the reservoir (m^3). In the IMWA model, there are two subsets of decision variables: those that must be determined before the realizations of random variables are disclosed (i.e. $WD_t^{\pm}$), and those that can be determined after the realized random-variable values are available (i.e. $WS_{tk}^{\pm}$).