Journal of Hydrology 537 (2016) 408–418

Contents lists available at ScienceDirect

Journal of Hydrology

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

A credibility-based chance-constrained optimization model for integrated agricultural and water resources management: A case study in South Central China

Hongwei Lu [a,b], Peng Du [a], Yizhong Chen [a], Li He [a,b,*]

[a] *School of Renewable Energy, North China Electric Power University, Beijing 102206, China*
[b] *State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China*

ARTICLE INFO

Article history:
Received 16 January 2016
Received in revised form 24 March 2016
Accepted 28 March 2016
Available online 4 April 2016
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Agricultural irrigation
Water resources management
Credibility
Fuzzy

SUMMARY

This study presents a credibility-based chance-constrained optimization model for integrated agricultural irrigation and water resources management. The model not only deals with parameter uncertainty represented as fuzzy sets, but also provides a credibility level which indicates the confidence level of the generated optimal management strategies. The model is used on a real-world case study in South Central China. Results from the case study reveal that: (1) a reduction in credibility level would result in an increasing planting area of watermelon, but impaired the planting acreage of high-quality rice and silk; (2) groundwater allocation would be prioritized for reducing surface water utilization cost; (3) the actual phosphorus and nitrogen emissions reached their limit values in most of the zones over the planning horizon (i.e., phosphorus and nitrogen emissions reaching 969 tonnes and 3814 tonnes under $\lambda = 1.00$, respectively; phosphorus and nitrogen emissions reaching 972 tonnes and 3891 tonnes under $\lambda = 0.70$, respectively). When the credibility level reduces from 1.00 to 0.70, system benefit would rise by 32.60% and groundwater consumption would be reduced by 79.51%. However, the pollutant discharge would not increase as expected, which would be reduced by 40.14% on the contrary. If system benefit is not of major concern, an aggressive strategy is suggested by selecting a rather low credibility level (say, 0.70). This strategy is suggested for guaranteeing protection of local groundwater resources and mitigation of local environmental deterioration by sacrificing part of system benefit.

1. Introduction

Water shortage and agricultural non-point source (NPS) pollution are main problems that restrict sustainable agricultural development. (Tuppad et al., 2010; Liu et al., 2011, 2016; Lam et al., 2013; Bryan and Kandulu, 2011; Duncan, 2014; Huang et al., 2015; Petit et al., 2015). In rural areas, economic development coupled with demographic growth have enlarged the gap between agricultural water supply and demand. This can lead to a serious water shortage (Toumi et al., 2016). Irrigation water shortage is profoundly affecting agricultural production in China. During the period of the 10th Five-Year Plan, the shortage of irrigation water was 3.00×10^{10} m^3 (Ma and Fang, 2006; Wang, 2010). NPS pollution, especially agricultural NPS pollution, has become a major factor of water pollution along with point source pollution gradually being controlled in recent years (Cai and Ringler, 2007; Duchemin and Hoger, 2009; Ouyang et al., 2010, 2013; Guo et al., 2014; Wesström et al., 2014). The combination of water shortage and the adverse impact of NPS pollution had evidently hindered sustainable agricultural development and further exacerbated the national food security, especially in rural areas, where agriculture is the major contributor to the local economy. For example, in China, nearly 0.26×10^6 ha of farmlands were suffering from the drought and being contaminated, which caused an annual reduction in the yield of grains by 35.00×10^{10} kg. What more serious is that less water is allocated to the agricultural system due to the continuous increase in domestic, industrial and ecological demand in the coming years. The expected water consumption used for agricultural will be kept below 44.00% by 2020 (Chinese Academy of Sciences, 2007). The lack of knowledge on scientific management and the rational use of limited resources further worsen the crises in rural Chinese regions. Crop planting structure optimization and holistic irrigation management improvement are potential solutions (Lu et al., 2009a,b; Regulwar

---

[*] Corresponding author at: School of Renewable Energy, North China Electric Power University, Beijing 102206, China. Tel./fax: +86 10 61772416.
E-mail address: li.he@ncepu.edu.cn (L. He).

http://dx.doi.org/10.1016/j.jhydrol.2016.03.056
0022-1694/

and Gurav, 2011; J.Q. Zhang et al., 2014; Y.M. Zhang et al., 2014; Pinela et al., 2016). These solutions can extensively promote reasonable water allocation and utilization, effectively control agricultural NPS pollution, and significantly ease the agricultural crises.

Many previous studies used mathematics in agricultural systems management (Balbi et al., 2015; Oeurng et al., 2011; Oliver-Rodríguez et al., 2015; Ramadas and Govindaraju, 2015; Sun et al., 2016; Wittmer et al., 2016). Sharifi and Van Keulen (1994) developed a dynamic land use planning system at the farm enterprise level. Lu et al. (2004) combined ecological production principles, simulation modeling, and multiple-goal linear programming as tools to explore land use strategies for the Loess Plateau in northern China. Santé and Crecente (2007) studied rural land use allocation in the Terra Chá district of Galicia using multi-objective linear programming methods to explore reasonable land use options. Singh and Panda (2012) developed a linear programming model for land use optimization to maximize net annual returns in the Haryana State of India. Afshar et al. (1991) presented a mixed-integer linear optimization model for the development of river basins for irrigation to improve agricultural water resource allocation. Zander and Kächele (1999) presented a multiple-objectives model to determine a method for sustainable development between agriculture and the environment. Qi and Altinakar (2011) used a multi-objective function to minimize sediment yields and nutrient concentrations and to maximize water quality and production benefits for agriculture. Klein et al. (2013) designed a multi-objective optimization routine that integrates a generic crop model and two climate scenarios for 2050 with limited water resources to adapt to climate change. Li et al. (2014) developed an inexact stochastic optimization model for the agricultural irrigation management of a case study in China. Previous studies based on various mathematical techniques had contributed to the development of the agricultural management policy, and further promote the sustainable development of agriculture.

Sustainable agricultural development requires long-term development strategies for agricultural activities to maintain balance among agricultural economy development, resources, and environmental protection by system optimization (Ward et al., 2013; Gandolfi et al., 2014; J.Q. Zhang et al., 2014; Y.M. Zhang et al., 2014; Kragt et al., 2016). Surface water resources, as an important water source, are unstable and difficult to predict accurately because of hardly-identified system components, such as natural, social and environmental factors. Groundwater is a type of stable water resources, which can be viewed as a significant supplement meeting water demands of agricultural system. But using groundwater alone as agricultural water source is likely to deplete groundwater. Therefore, the conjunctive use of surface and ground water resources is a potential solution to meet the continuously stable demands in many semi-arid regions (Lu et al., 2009a,b). Agricultural NPS pollution is a worldwide problem because of its asymmetric information, high uncertainty, randomness, moral hazard, and adverse selection (Canton et al., 2009), particularly in China, where land use is dispersed among farm households. Total amount control is an applicable measure for quantifying and managing agricultural NPS pollutions for large agricultural systems, and helps achieve regional agricultural environmental standards (He et al., 2008a; J.Q. Zhang et al., 2014; Y.M. Zhang et al., 2014).

However, various uncertain factors may influence on an agricultural system, such as water availability, agricultural water demand, and pollutants discharge into water. These parameters have been frequently expressed as fuzzy sets if sufficient statistical information is unavailable for parameter estimation. Possibility-constrained programming has proven to be a good tool to solve the water management problem where both left- and right-hand-side coefficients are fuzzy sets (He et al., 2008b). As a matter of fact, this problem can also be solved by credibility-constrained programming. As proposed by Liu and Liu (2002), credibility is a more reasonable fuzzy inequality indicator than possibility and necessity because it compensates for their disadvantages. Nevertheless, very few studies have attempted to use credibility-constrained programming to solve such problem.

The main objective of this study is to formulate a credibility-based chance-constrained optimization model by replacing the traditional concept of possibility with credibility for measuring a fuzzy event (or fuzzy inequality). The model is capable of not only dealing with parameter uncertainty represented as fuzzy sets, but also providing a credibility level that indicates the level of confidence of the generated optimal management strategies. From the agricultural system planner perspective, the developed model with credibility concerns is believed to be more appropriate. The model was used in a real-world case study in South Central China. This study involves an agricultural system wherein various agricultural activities were planned to maximize benefits. Surface and groundwater were conjunctively used for irrigation, and agricultural NPS pollution was controlled by total amount control. This study is the first attempt to use the concept of credibility for addressing parameter uncertainty. Two scenarios were established to examine the variations of optimized agricultural management strategies with pre-determined credibility levels (i.e., λ). The framework of this study is illustrated in Fig. 1.

2. An agricultural system in Yongxin, China

2.1. Overview of the study region

The study region is in the western part of Jiangxi Province, China (Fig. 2). Its topography mainly consists of hills and mountains. Agriculture and forestry are the main industries in this county. The land users in the study area are farm households, whereas the decision maker is the agricultural system planner. The Heshui River flows through the study region and is a major water source for agricultural irrigation. Groundwater from the local aquifer is the other water source. Serious environmental problems, such as (1) irrigation shortages caused by unreasonable crop planting structure and water utilization patterns and (2) excessive fertilizer and pesticide usage, which leads to serious agricultural NPS pollution. NPS pollution contributes to eutrophication, and persistent pollution in local water bodies exist because of inappropriate agricultural practices and the lack of environmental awareness. These problems threaten the surrounding ecosystems and public health and hinder sustainable agricultural development. An effective land use and water resource management system and efficient agricultural NPS pollution control are needed to guide agricultural system planners in initiating sustainable agricultural systems management strategies to alleviate the existing conflict between water supply and demand as well as to assist agricultural NPS pollution control.

2.2. Statement of the problems

The local agricultural development plan states that the study area is planted with eight kinds of crops, including hybrid rice, glutinous rice high-quality rice, watermelon, sweet potato, tea, rapeseed, and silk, to maintain balance between cash and food crops. The planning horizon is allotted 25 years, which is divided into five stages composed of five consecutive years each. The study region consists of five zones and the total area available for agricultural crops decreases by 2.00% in each period, according to the local land-use planning. The acreage of the eight crops must be greater than the planning level in the different planning zones to ensure