Applied Mathematical Modelling 38 (2014) 5502–5514

Contents lists available at ScienceDirect

Applied Mathematical Modelling

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

A fuzzy inexact two-phase programming approach to solving optimal allocation problems in water resources management

Bin Shi, Hong-wei Lu *, Li-xia Ren, Li He

College of Renewable Energy, North China Electric Power University, Beijing 102206, China

ARTICLE INFO

Article history:
Received 20 October 2012
Received in revised form 11 December 2013
Accepted 3 April 2014
Available online 13 April 2014

Keywords:
Agricultural irrigation planning
Interval
Uncertainty
Two-phase
Environmental standard
Water resources management

ABSTRACT

Inappropriate agricultural activities are the main reasons of water shortage and environmental pollution in many rural areas. How to generate preferred decision schemes for agricultural activities is a critical issue for decision makers. In this study, a two-phase programming approach is advanced for regional water resources allocation in a rural region of China. The approach shows applicability when the uncertain inputs are provided as intervals and such uncertainty is desired to be delivered to the corresponding solutions. Multiple control variables are introduced both in the objective function and constraints of the programming model, which make it possible for the constraints being relaxed under respective levels. A more satisfactory objective value can thus be expected as well as the impact of each constraint on the modeling outputs can be clarified effectively. The decision variables are useful for decision makers to justify and/or adjust the decision schemes for agricultural activities through incorporation of their implicit knowledge on water allocation management.

1. Introduction

Water resources management systems are associated with various activities and objectives with complicated supply–demand conflicts [1]. Competitive water allocation issues among various end-users have become major topics for many researchers [2]. Such issues are particularly aggravated in agricultural irrigation systems where multiple water users exist along with relatively low water availability and stability [3]. So how to allocate the limited water resources to satisfy agricultural irrigation demands in the most cost-effective and environment-friendly manner becomes much urgent for decision makers and stakeholders [4].

Previously, a number of regional models were proposed for integrated management of water resources. For example, Ortega et al. [5] provided a simple methodology for analyzing the effect of water-utilization cost on the crops in a Spanish semi-arid region. Fassio et al. [6] developed a decision support system for assessing alternative measures for the reduction of nitrogen pressure from agriculture on water resources at a European level. Laxmi et al. [7] advanced a deterministic linear programming (DLP) and a chance-constrained linear programming (CCLP) models to allocate available land and water resources optimally in eastern India. Gaiser et al. [8] proposed an integrated model for water resources management in the Ouémé basin. Mula et al. [9] carried on the practices of water allocation among smallholders in the South Pare

* Corresponding author. Tel.: +86 10 61772939.
E-mail address: luhw@ncepu.edu.cn (H.-w. Lu).

http://dx.doi.org/10.1016/j.apm.2014.04.005

Mountains, Tanzania. Lange et al. [10] used a water-use simulation model based on GIS and applied to an agricultural irrigation sector in the Inkomati Water Management Area in South Africa.

However, uncertainties widely exist in system components that intensify the complexity of water management problems in most real-world practices [11–17]. Many system components may present spatial and temporal variations (i.e., parameter uncertainty), and their interactions may further compound the above complexity (i.e., stipulation uncertainty) [18]. These induced many inexact programming methods having been developed in recent years. In terms of parameter uncertainty, Davila et al. [19] proposed a grey integer programming-based game for the landfill space consumption dynamics in the Lower Rio Grande Valley under uncertainty. Anand et al. [20] developed a system dynamics approach for regional environmental planning and management. Karmakar and Mujumdar [21] suggested a grey fuzzy optimization programming method for water quality management of a river system, in order to address uncertainty involved in fixing the membership functions for different goals of the pollution control agency and dischargers. Peidro et al. [22] introduced a fuzzy linear programming based on the tactical supply chain planning approach for environment management under uncertainty.

Stipulation uncertainties may also exist in many problems, where the relationships between right- and left-hand sides of the formulation's constraint cannot be completely satisfied [23,24]. In order to deal with such issues, a number of fuzzy flexible programming approaches were developed. For example, Chen and Huang [25] proposed a Newton-like method for solving quadratic stochastic programs. Chen et al. [26] extended the conventional quadratic programming (IQP) for environmental systems analysis. Karsak et al. [27] studied a fuzzy multi-objective programming approach to facilitate decision making in the selection of a flexible system. Tan et al. [28] suggested an inexact fuzzy robust programming model for integrated evacuation management under uncertainty; fuzzy relations between right- and left-hand-side constraints of the integrated model were addressed by means of a fuzzy flexible programming framework as well as its solution method. In general, these approaches were all based on an assumption that the uncertain features of left-hand-side coefficients for each constraint were dependent upon each other, such that each constraint was represented as a fuzzy set and then a general control variable (λ) was used for indicating the satisfactory level of model solutions [29–31]. Apparently, these assumptions may not be true in all practical problems and may render a portion of constraints being not well-satisfied but the others being over-satisfied. One potential solution is to introduce multiple control variables respectively corresponding to every constraint, in order to represent various relaxation levels to the objective function and stipulations. Lu et al. [23] developed an enhanced fuzzy optimization model based on inexact air dispersion simulation for regional air quality control, in which multiple control variables were integrated to the objective function and constraints. The model and the provided solution method showed advantages in handling the above stipulation uncertainty according to the case study; the successful application also indicated that the approach could be extended to other environment systems upon some supplementary efforts.

In this study, a two-phase programming approach will be developed for the water allocation problem in Yongxin, China. Multiple control variables will be considered in a two-phase procedure to make different relaxation levels for the objective function and constraints of the programming model. This may efficiently address various stipulation uncertainties embedded in each constraint, compared with the previous achievements that such uncertainties were assumed to be the same so that only one control variable was used to reflect it. It will also help reflect their special characteristics and particular impacts on the system. Besides, parameter uncertainty will also be considered through introducing interval programming approaches. By these means, both stipulation and parameter uncertainties can be addressed in the new approach. In the modeling framework, a number of social, economic and environmental constraints will be involved in consideration of the practical conditions of the study system.

2. Overview of the system

2.1. Topographic condition

This study case is located in the western part of Jiangxi Province, China (Fig. 1). It belongs to the middle part of Luoxiao Mountain and the middle reaches of the Heshui watershed. The area ranges in longitude from 113°50′ to 114°19′E, and in latitude from 26°14′ to 27°14′N. The study region is 65 km from east to west and 56 km from north to south, with the total area being 2190 km^2, approximately. Within the region, the topography comprises a higher western area (i.e., mountains) and a lower eastern area (i.e., hilly land).

2.2. Climatic condition

The region belongs to the subtropical and seasonal wind climate, with high heat and rainfall coming in summer seasons. The intensely varied climate always brings low temperatures, floods, droughts, dry hot winds, and cold dew winds, which lead to more difficulties for agricultural activities. The average sunlight is 1787.9 h/yr, with the highest sunlight occurring in July and August. As for the daily level, sunlight is guaranteed for 61% of each summer day, while only 39% in each winter day. The average temperature of the County is 18.2 °C. July and August usually have the highest temperatures (i.e., between 28 and 29 °C), while January is the lowest month (i.e., around 6.4 °C). The recorded highest temperature was 40 °C in both 1963 and 1967, and the coldest was –6.6 °C in January 1967. The County enjoys an average of 281 frost-free days each year.