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A robust optimization modelling approach for managing water and farmland use between anthropogenic modification and ecosystems protection under uncertainties

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A B S T R A C T

In this study, a dual inexact fuzzy radial chance-constrained programming (DIFRCCP) method was developed for planning water and farmland use management system with the consideration of the conflicts between anthropogenic modification and ecosystems protection. This method can effectively reflect and tackle the multiple uncertainties existing in water and farmland use activities and eco-environmental management, which can be expressed as regular and radial intervals, random boundary interval (RBI) and fuzzy sets. Particularly, it could ensure solutions feasible and near optimal with high probability when the data changes within a certain bound radii of ecological parameters. Meanwhile, the correlation consisting between the lower and upper bounds of RBI (i.e., water supply parameters) can get solved by the joint probability distribution function, further strengthening the robustness of developed model. Through computing the proposed model, the generated solutions could provide detail water and farmland use management plans between anthropogenic modification and ecosystems protection for decision makers, including farmland use arrangement, water allocations to various consumers, as well as ecological and environmental pollution control through balancing the tradeoffs among system profits, the probability of constraints violation and system reliability under reasonable protection levels and satisfaction degrees.

1. Introduction

Population growth, social development and ecological protection represent significant pressures on water and farmland resources. Also, extensive soil disturbance and application of fertilizer and manure in agriculture cause nonpoint source (NPS) losses of soil and nutrients such as nitrogen and phosphorus, further resulting in increased pollution problems in many receiving water bodies (Zhang et al., 2009a,b). All these problems require water managers to consider a wider array of management options that account for economic, social, and ecological factors to properly manage water and farmland resources between anthropogenic modification and ecosystems protection (Willuweit and O'Sullivan, 2013).

In the past decades, many efforts have been done to plan the water and farmland use through balancing the conflicts between anthropogenic modification and ecosystems protection. In the past decades, many efforts have been done to plan the water and farmland use (Trepel and Palmeri, 2002; Wang et al., 2006; Larsen et al., 2007; Adeyemo and Otieno, 2010; Wang et al., 2011; Sanon et al., 2012; Scannapieco et al., 2012; Dutta et al., 2013; Everaert et al., 2013; La Rosa and Privitera, 2013; Vidal-Legaz et al., 2013; Yu et al., 2013). For example, Larsen et al. (2007) used a process-based geomorphic simulation modelling to forecast potential long-term landscape-level effects of water management decisions on river meander migration to avoid the conflict between wildlife-dependent riparian ecosystems and adjacent human infrastructure (e.g., towns, bridges, water pumps, etc.). Jia et al. carried on an urban wetland planning in Beijing central region for determining the acreage and spatial location of each type of urban wetlands and estimating ecological water requirement.

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Wang et al. (2011) explored a Social–Economic–Natural Complex Ecosystem (SENCE) approach for eco-sustainability planning and management. Sanon et al. (2012) applied trade-off and multi criteria decision analysis to analyze and quantify the explicit trade-offs between the stakeholder's objectives related to management options for the restoration of an urban floodplain, the Lobau, in Austria. Vidal-Legaz et al. (2013) built a dynamic simulation model to calculate the trade-offs between the provisions of two ecosystem services, landscape aesthetic value and water supply for human use and the economic development associated with different land use changes. La Rosa and Privitera (2013) proposed a land-use suitability strategy to enhance the production of ecosystem services and define new appropriate land-uses for non-urbanized areas (NUAs) within the agricultural and green infrastructure in three municipalities of Italy.

However, water and farmland resource systems are sensitive to climate and population changes, which are causing an increasing awareness of uncertainties involved in policy making and long-term planning, and their impacts on policy success. Furthermore, intricate interactions existing between various subsystems (e.g., conflicts between anthropogenic modification and ecosystems protection upon water and land resources) will inevitably produce a variety of uncertainties. Additionally, subjective judgments obtained from experts and stakeholders who are involved in the management process exert significant impacts on data acquisition and system reliability. These complexities lead to difficulties in solving the resulted uncertain optimization problems. Therefore, robustly planning models need to confront and settle these uncertainties and dynamics in a changing and complex environment (Hermans et al., 2012; Matrosov et al., 2013).

In the previous studies, a number of inexact planning methods have been applied into water and farmland use management system with the consideration of conflicts between anthropogenic modification and ecosystems protection, tackling the inherent uncertainty of future conditions (Matrosov et al., 2013), such as interval linear programming (ILP), fuzzy linear programming (FLP), stochastic linear programming (SLP), as well as robust programming (RP) (Huang, 1996, 1998; Watkins et al., 2000; Sethi et al., 2006; Zhang et al., 2009a,b; Lv et al., 2013; Tairaj and Vedula, 2000; Virjee and Gaskin, 2005; Altunkaynak and Şen, 2007; Eiger and Shamir, 1991; Altunkaynak et al., 2005; Maqsood et al., 2005; Wang and Huang, 2012; Cai et al., 2011, 2012). Specifically, Huang (1996) developed an interval parameter water quality management (IPWM) model and applied to a case study of water pollution control planning to examine their likely impact on agricultural ecosystems. Huang (1998) proposed an inexact-stochastic water management (ISWM) model for agricultural ecosystem management based on an inexact chance-constrained programming (ICCP) method. Watkins et al. (2000) employed a scenario-based, multistage stochastic programming model for the planning of the Highland Lakes in Central Texas. To avoid the conflicts between ecosystems protection and anthropogenic modification, Sethi et al. (2006) adopted the deterministic linear programming (DLP) and chance-constrained linear programming (CCLP) models to optimally allocate available land and water resources and provide a set of long-term sustainable land and water management strategies. Zhang et al. (2009a,b) introduced an inexact-stochastic dual water supply programming (ISDWSP) model based on the analysis of inexact characteristics in demand and supply subsystems of dual water supply system and their dynamic interactions with ecosystem variations. Lv et al. (2013) developed a scenario-based interval two-phase fuzzy programming (SITF) method for water resources planning in a wetland ecosystem. Tairaj and Vedula (2000) used fuzzy linear programming in modelling a three reservoir system in the Upper Cauvery River basin, South India through treating uncertainties in reservoir inflows as fuzzy sets. Virjee and Gaskin (2005) developed a cost recovery criterion system using fuzzy set theory in planning sustainable water supply systems in several developing countries to identify the trade-offs between linked ecosystem services and stakeholders' activities. Altunkaynak and Şen (2007) introduced fuzzy membership functions to evaluate the dynamic valuation of ecosystem services in the Lake Van, eastern Turkey. Maqsood et al. (2005) presented an interval-parameter fuzzy two-stage stochastic programming (IFTSP) method for the planning of water resources and ecological environment management systems under uncertainty. Wang and Huang (2012) exploited an interactive multi-stage stochastic fuzzy programming (IMSFP) approach for identifying optimal water resources allocation strategies.

Overall, among these technologies for modelling water and farmland use management systems between anthropogenic modification and ecosystems protection under uncertainties, the introduction of interval linear programming (ILP), stochastic linear programming (SLP) and fuzzy linear programming (FLP) into a general modelling framework can be effective to reflect uncertain information in terms of intervals, distributions and fuzziness. However, specifically, ILP is based on crisp interval values when the lower and upper bounds are known. So far, SLP requires a set of restrictive assumptions and numerical data with known probability distributions for their verifications. Besides that, the assumptions of fuzzy approaches are generally for idealization of the concerning phenomenon that human can understand the problem at its simplest level with the current knowledge (Şen and Altunkaynak, 2009). That is to say, ILP, SLP and FLP all have the weakness of assuming the range of input data equals to a number of nominal values. This means that the nominal value of each bound of an interval parameter (e.g., the allowed amount of soil loss) may fluctuate within a radius. This will directly cause several constraints be violated and the solutions may no longer be optimal or even feasible when the practical data are inconsistent with the nominal values (Dong et al., 2013). Apart from this, in reality, water resource availability is sensitive to geographical conditions and climate change, as well as utilization efficiency. Thus, it will be hard to acquire lower and upper bounds of water resource availability in a deterministic format when the lower and upper bounds are correlated. This leads to dual uncertainties. In the past decades, few works were conducted to handle these types of uncertainties existing in the processes of water and farmland use planning, which might result in missed information and thus impractical decision support (Cao et al., 2010).

Therefore, in this study, the concepts of radial parameter theory and random boundary interval (RBI) will be introduced to tackle these dual uncertainties. To be specific, the radial parameter can be defined as an interval number with each of its bounds being a nominal value fluctuating within a radius. It will be used to generate feasible and near optimal solutions under data changes through the adoption of robust optimization (RP). In RP, the concept of protection level is introduced to protect against violation of constraints and ensure robust solutions be feasible with high a probability. The conservativeness of solutions can get adjusted via probability bounds of constraint violations, helping satisfy ecological–environmental and economic requirements (Tan et al., 2010a,b, 2011). Furthermore, the lower and upper bounds of RBI (e.g., interval value of water resource availability) are continuous random variables, where the distribution information of streams can be incorporated into the model. The correlation exits between lower and upper bounds can thus be tackled in RBI through the adoption of a joint probability distribution function.

Finally, the proposed radial parameter and RBI theory will be integrated with ILP, CCP and FLP methods, creating a dual