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Agricultural effluent control under uncertainty: An inexact double-sided fuzzy chance-constrained model

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ABSTRACT

An inexact double-sided fuzzy chance-constrained programming (IDFCCP) method was developed in this study and applied to an agricultural effluent control management problem. IDFCCP was formulated through incorporating interval linear programming (ILP) into a double-sided fuzzy chance-constrained programming (DFCCP) framework, and could be used to deal with uncertainties expressed as not only possibility distributions associated with both left- and right-hand-side components of constraints but also discrete intervals in the objective function. The study results indicated that IDFCCP allowed violation of system constraints at specified confidence levels, where each confidence level consisted of two reliability scenarios. This could lead to model solutions with high system benefits under acceptable risk magnitudes. Furthermore, the introduction of ILP allowed uncertain information presented as discrete intervals to be communicated into the optimization process, such that a variety of decision alternatives can be generated by adjusting the decision-variable values within their intervals. The proposed model could help decision makers establish various production patterns with cost-effective water quality management schemes under complex uncertainties, and gain in-depth insights into the trade-offs between system economy and reliability.

1. Introduction

Agricultural system has been a major concern for almost one country since it not only gives necessities of human-living and promotes socio-economic development, but also poses a serious threat to ambient environmental quality and resource conservation [34]. Nowadays, problems associated with water shortage and water quality degradation continue to be a major challenge for agricultural communities throughout the world. For example, a significant amount of nitrogen and phosphorus may be released from applied fertilizer and manure, leading to a rapid increase of nitrogen and phosphorus concentrations in the receiving water bodies; irrigation would consume a huge amount of water which could exacerbate water-shortage problems under disadvantageous conditions (e.g. dry season) [34]. In order to solve the above problems, a sound water quality management scheme is necessary. Generally, water quality management planning covers a number of aspects related to economic development, environmental impact, resources conservation and political consideration [22,45]. These processes were associated with extensive uncertainties due to their complex, interactive, dynamic, and multi-objective features [11]. Such uncertainties would bring significant difficulties in formulating and solving water quality management problems. It is thus desired that optimization models be developed for dealing with such a difficulty.

Over the past decades, a large number of inexact optimization techniques were developed to deal with uncertainties in water quality management under uncertainty [1,3,6,8,24,31,36,39,40,52]. The majority of these methods were related to stochastic mathematical programming (SMP) [12,26,27,41], fuzzy mathematical programming (FMP) [5,10,14,25,27,32,35,50] and interval linear programming (ILP) [15,16]. Among them, SMP could deal with the probabilistic uncertainties and generate a series of explicit solutions presented as probability distributions. However, the rigorous data requirement to specify parameter probability distributions and intensive computational burden would lead to difficulties in its practical applications [30]. FMP handles fuzzy variables in a variety of ways, such as fuzzy flexible programming (FFP) [18,32,37,48], fuzzy possibilistic programming (FPP) [43,52], and fuzzy robust programming (FRP) [28,30,34]. FFP and FPP require that some intermediate variables be introduced into the solution process; this would lead to complicated intermediate models and significantly increase computational burden [23]. FRP delimits an uncertain decision space by specifying uncertainties through dimensional enlargement of the original fuzzy constraints, and thus enhances the robustness of the optimization process [28]. However, the main limitation of the FRP lies within its deterministic coefficients for the objective function, leading to potential losses of valuable uncertain information [30]. ILP can tackle

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all uncertain parameters presented as intervals without any distribution information. However, it doesn't allow any violation of system constraints and might become infeasible when the right-hand-side parameters in constraints were highly uncertain [18].

Recently, the chance-constrained programming with fuzzy parameters (i.e. FCCP) has been presented as a novel FMP method through incorporating some predefined confidence levels of fuzzy-constraints-satisfaction into optimization models [29]. Similar to stochastic chance-constrained programming (SCCP) models, FCCP requires that the fuzzy constraints be transformed to deterministic ones at predetermined confidence levels [29]. Compared with other FMP methods, FCCP has a relatively low computational requirement and could obtain a series of solutions leading to high system benefits at allowable violation risk levels. Previously, FCCP have been successfully used in many applications [2,29,38,40]. However, in most of these applications, the applied methods could only deal with fuzzy uncertainties in the right-hand sides of model constraints (i.e. single-sided FCCP). In many real-world management problems, it is more common that both sides of model constraints will be associated with uncertainties (i.e. double-sided FCCP). Thus, it is desired that more competent FCCP methods be advanced. In addition, FCCP may encounter difficulties in obtaining fuzzy distribution information due to lack of data or difficulties in obtaining the data. Such type of uncertainties may be associated with objective functions and part of the model constraints.

Interval linear programming (ILP) is an alternative for handling uncertainties which are expressed as discrete intervals [49]. It has the lowest requirement on data quality and uses only the boundary information of parameters to reflect uncertainties that are hardly describable in either fuzzy or stochastic formats. Applications of ILP can be referred to [17–19,37,46–48]. From these studies, the major limitations of ILP are that it doesn't allow any violation of the system constraints and may become infeasible when the right-hand side parameters in constraints are highly uncertain [18]. FCCP is effective for mitigating such problems by introducing fuzzy chance-constraints, but weak in tackling additional uncertainties that cannot be described by fuzzy sets. The two methods have varied strengths and weaknesses, with a potential for compensating each other when they are integrated within a general framework.

Based on the above-mentioned facts, this study aims to develop an innovative model, namely inexact double-sided fuzzy chance-constrained programming (IDFCCP) model, for tackling complex uncertainties associated with water quality management systems. It will be a hybrid of ILP and double-sided fuzzy chance-constrained programming (DFCCP), and is mostly effective in dealing with uncertainties expressed as both fuzzy sets and discrete intervals. It is the first attempt to enhance conventional FCCP by extending its capacities for dealing with multiple uncertainties and addressing a full range of uncertain parameters in both sides of model constraints. A water quality management case will be used to demonstrate the applicability of the proposed method.

2. Agricultural water quality management under uncertainty

Agricultural production needs water for irrigation purpose, and generates nonpoint source pollutants due to manure/fertilizer applications [13]. This will lead to severe shortage of water resources and degradation of water quality. In fact, the improvement of the water quality could more or less increase the amount of available water resources, and mitigate the water-shortage problems. This is mainly due to the fact that the improvement of water quality can extend its applicability to wider ranges. For example, some sewage after treatment may satisfy the water quality standard for scenery and recreation purpose. This process of “Reusing” increases the available water amount and relieves the problem of water resources shortage. Therefore, a sound water quality management strategy is very important for agricultural development. Recently, there have been many environmental regulations (e.g. strict standards for pollutant discharge and environmental loading capacity) and water-saving technologies (e.g. technologies of improving water-utilization efficiency and cultivating low-water consuming crops) put into place by the government in order to save water resources. However, the goal of pure “zero pollution” or “zero consumption” is normally difficult to achieve. Therefore, determination of available water resources amount, establishment of feasible discharge levels of the pollutants and definition of the environmental loading capacities are principal tasks for the local authorities and water managers. To obtain cost-effective management strategies in consideration of the above-mentioned limitations, optimization models are needed.

Fig. 1 shows the conventional procedures of establishing an optimization model for supporting agricultural water quality management. The first step is to investigate and analyze the related information within an agricultural system. Such information may include the capacities of crop cultivation and livestock breeding, the unit amount of pollutants (e.g. N or P) from applied manures and fertilizers, the available discharge standards and the required environmental loading capacities. The next step is to define system boundary, planning target and restrictive conditions, and determine optimization approaches according to system characteristics. The final step is to formulate and solve the optimization model, aiming to maximize net benefit and balance system economy and reliability. The obtained solutions will provide important decision supports for the related water managers.

However, a typical water quality management system involves a number of processes and factors, and these processes are subjected to many considerations. Due to the multi-period, multi-layer and multi-objective features associated with these factors and their interactions, extensive uncertainties may exist [34,45]. Depending on the quality of data, different uncertainty-analysis methods can be used. Among various alternatives, SMP is mainly used to tackle uncertainties expressed as random variables with probabilistic distribution functions. The critical step of using SMP is to generate probabilistic distribution functions through analyzing long-term historical data. In water quality management system, the available water amount may exhibit random characteristic and can normally be presented by probabilistic distribution functions (PDFs) based on long-term time-series hydrological data. FMP can handle data that show features of vagueness and imprecision; they are normally estimated empirically. In agricultural water quality management, parameters related to environmental loading capacities (such as allowable soil loss and pollutants discharge amounts) are subject to human judgments, and could better be expressed by fuzzy membership functions. ILP can represent uncertainties as discrete intervals and is effective in situations when little information is available. In agricultural system, many parameters (such as the unit yield of crops and the unit benefit of livestock) suffer from a lack of complete data survey, and they are more suitable to be described by discrete intervals.

In practical applications of agricultural water quality management, the information of the available water amount is hardly sufficient to help generate its probability distribution. Even if the stochastic distribution functions are available, it is still difficult and time-consuming to solve a large-scale SMP model [21]. FMP uses expert opinion or public survey to define fuzzy possibility distributions and the related data requirement is much less than that of SMP. ILP is another alternative in dealing with uncertainties with least amount of information. However, the process of collecting and analyzing fuzzy information sometimes is time-consuming and requires additional manpower in many practical applications; ILP only considers the extreme conditions of an uncertain event and is incapable of providing richer information for decision makers than fuzzy approaches. In fact, the agricultural water quality management system involves many uncertain parameters with different data