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An inexact simulation-based stochastic optimization method for identifying effluent trading strategies of agricultural nonpoint sources

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ABSTRACT

Agricultural nonpoint sources (NPS) pollution has long been regarded as the leading challenge in maintaining water quality of receiving water bodies. Effluent trading can serve as a cost-effective way to achieve optimal configuration of discharge permits in agricultural NPS pollution control. However, great difficulties exist in practical effluent trading planning, including uncertainties related to randomness and imprecision, system risk of nutrient loadings being unacceptably high, and factors with spatiotemporal heterogeneity within the watershed. In this study, an inexact simulation-based stochastic optimization method (ISSOM) is developed for identifying effluent trading strategies in response to the above challenges. With the aid of technique of interval analysis, uncertain parameters related to nutrient yields can be handled and dynamic variation of NPS contaminant loadings can be reasonably addressed. Besides, ISSOM can tackle uncertainties expressed as fuzzy, stochastic and interval formats and capture the notion of risk under high-variability situation in NPS pollution control. The ISSOM is applied to a real case of agricultural NPS pollution mitigation through effluent trading in Xiangxihe Watershed. Results show that the uncertainties play a major role in successfully launching an effluent trading program, and trading scheme can mitigate agricultural NPS pollution with an increased system benefit. Results also reveal that the agricultural zones of Xiakou and Gufu are the major pollution sources and main purchasers in effluent trading, and Guizhou zone is the main vendor which contributes least to nutrient discharge. These findings can not only facilitate identification of the main pollution sources and optimal effluent trading schemes, but also gain insight into the tradeoff among the agricultural benefit, system risk, and satisfaction degree.

1. Introduction

Nonpoint sources (NPS) pollution has long been regarded as the leading challenge in maintaining water quality of receiving water bodies, with agriculture being the largest contributor (Dowd et al., 2008; Shan et al., 2014). The problem of water quality degradation has been recognized as a possible consequence of ever-increasing utilization of fertilizers for boosting the agricultural production. Developing effective measures, such as water quality zoning, waste-load allocation, and effluent trading, with the concerns of agricultural economic benefit and NPS pollution control becomes a major priority for decision makers. Effluent trading is regarded as one of the most promising measures for water quality remediation, which provides a framework wherein pollutant discharge permits can be transferred among present or potential dischargers; thus optimal configuration of the permits can be achieved (Nishizawa, 2003). In addition, effluent trading can serve as a cost-effective way to support the decision-making in pollution abatement by allowing one source to meet its regulatory obligations by using discharge permits of another source that has lower environmental cost (Ning and Chang, 2007). However, in practical effluent trading, the outcome has not always been considered feasible due to various uncertainties; they can be attributed to two origins which are randomness and imprecision. Randomness results from natural variability of the observed nutrient loadings with heterogeneity. Imprecision is derived from the lack of information associated with systematic measurement error or expert

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opinion (Li et al., 2014a). As a result, a number of inexact optimization methods have been advanced for effectively addressing the uncertainties in agricultural NPS pollution mitigation.

A number of efforts were made in developing fuzzy and stochastic mathematical programming methods for water quality management under uncertainty, where economic targets were designed as indicators to examine competitive effluent-dischargers (Ganji et al., 2007; Zhang et al., 2009; Nahorski and Horabik, 2010; Nikoo et al., 2012, 2013; Xu and Qin, 2013; Li et al., 2014b). For example, Luo et al. (2005) presented an inexact fuzzy two-stage stochastic programming model to quantify the efficiency of effluent trading efforts within land retirement programs for agricultural NPS pollution reduction under uncertainty; Niksokhan et al. (2009) presented a stochastic conflict resolution methodology for developing pollutant discharge permit trading in river systems, where the utility functions of decision makers and stakeholders of the system were related to the total treatment cost and a fuzzy risk of violating the water quality standards. Mesbah et al. (2010) proposed a discharge permit transference model through coupling an extended trading ratio system and a fuzzy nonlinear regression model, which could help consider the uncertainties in treatment cost function and provide decision makers with a wealth of cost-effective, technology oriented management strategies. Nikoo et al. (2014) linked particle swarm optimization technique and simulated annealing technique with stochastic dynamic programming model to optimize water and waste load allocation in reservoir–river systems considering the existing uncertainties in reservoir inflow, waste loads and water demands.

Among the above methods, two-stage stochastic programming (TSP) is effective for problems where an analysis of policy scenarios is desired and uncertainties are expressed as random variables with known probability distributions (Li et al., 2010). The fundamental idea behind TSP is the concept of recourse, which is the ability to take corrective actions after a random event has taken place. In TSP, a decision is first undertaken before values of random variables are disclosed and, then, after the random events have occurred and their values are known, a recourse action is made in order to minimize "penalties" that may appear due to any infeasibilities. The initial action is called the first-stage decision, and the corrective action is called the second-stage decision. The TSP modeling formulation can thus provide an effective linkage between the policies and the associated economic penalties caused by improper policies (Huang and Loucks, 2000; Li and Huang, 2009a). However, a potential limitation of the conventional TSP is that it can only account for the expected second-stage cost without any consideration on the variability of the recourse values (Ahmed and Sahinidis, 1998; Li and Huang, 2009b). Robust optimization (RO) is launched to penalize the second-stage cost that is above the expected value, as well as to capture the notion of risk in stochastic programming; unfortunately, few studies are reported on the application of RO techniques to effluent trading planning problems (Chen et al., 2012). In fact, in one effluent trading program, the quality of available information is often not satisfactory for establishing probability distributions of random parameters. The probability distributions are used to acquire the probabilities of nutrient loadings of different discharge levels. Then the optimization model can be linearized and solved through letting random nutrient loadings take discrete values with probability levels. Besides, decision makers may encounter difficulties while determining and allocating discharge allowances due to uncertainties arising from subjective interpretation and expert judgment. Moreover, economic data (e.g. agricultural benefit) is incomplete due to inexact factors and their interactions such as the agricultural product price and cost related to the utilization of electricity, fertilization, pesticide and plastic film as well as transportation, which may vacillate within a certain interval. The conventional RO methods have difficulties in dealing with uncertainties expressed as fuzzy sets and intervals. Therefore, it is desired that effective methods, which can tackle various uncertainties, be incorporated within the RO framework; this leads to an interval-fuzzy-based robust optimization (IFRO) method, such that uncertainties with varied presentation formats in effluent trading planning problems can be reflected.

On the other hand, optimal design of trading schemes may be significantly restricted by difficulties in simulating NPS solute transport processes. In fact, nutrients (in dissolved and/or particulate phases) may migrate into lower soil layers from which they can transport into water bodies with surface runoff, which usually presents a major pathway of nutrient emission (Shan et al., 2014). NPS pollution comes from diffuse sources and further depends on not only the agricultural activities of polluters, but also exogenous factors associated with spatiotemporal heterogeneity within the watershed such as precipitation, topography, surface runoff, land use, vegetation, and sediment generation. This makes the detected pollution level an imprecise measurement. Distributed simulation models are effective tools for analyzing nutrient transport behaviors and have evoked many researchers' interests in accounting for complicated physical process, analyzing climate effect, characterizing heterogeneous factors, modeling management practice, and metamodeling for computationally intensive problems (FitzHugh and Mackay, 2000; Børgesen et al., 2001; Ham et al., 2010; You et al., 2012; Villa-Vialaneix et al., 2012; Chen et al., 2013; López-Vicente et al., 2013; Chahor et al., 2014). For instance, Akhavan et al. (2010) modeled the amount and dynamics of nitrate leaching from a typical crop rotation in one watershed using soil and water assessment tool (SWAT), in which the calibration was conducted using crop yield to increase the confidence on soil moisture and evapotranspiration. Galelli et al. (2010) tested the design of a metamodel for planning the reservoir release policy via stochastic dynamic programming algorithm in Muzza–Bassa Lodigiana irrigation; the goal of metamodeling exercise was to strongly reduce the state dimensionality of the distributed-parameter model. Shen et al. (2012) examined the effect of rainfall spatial variability on watershed hydrology and NPS modeling of the Daning Watershed in China, where five interpolation methods were used to characterize the spatial rainfall variability. The conventional nutrient transport simulation techniques typically expressed all parameters for NPS modeling as deterministic values; however, practical nutrient transport process were complicated with complexities derived from spatiotemporal variations related to meteorology, soil type, land use, slope and agricultural management practice within the watershed. In response to such complexities, inexact simulation techniques were advanced for reflecting various uncertainties in NPS nutrient transport simulation (Chen and Mackay, 2004; Abbaspour et al., 2007; Wu and Liu, 2014). Nevertheless, little comprehensive analysis based on the integration of inexact simulation and optimization techniques was reported in supporting agricultural effluent trading planning.

Various uncertainties existing in system components, system risk resulting from the fluctuation of random variables, and heterogeneous factors within the watershed can pose great difficulties for practical effluent trading planning. Systems analysis methods for effectively dealing with such challenges are thus desired. Therefore, an inexact simulation-based stochastic optimization method (ISSOM) is developed for identifying effluent trading strategies of agricultural NPS in response to the above challenges. The ISSOM can enhance effluent trading through incorporation of IFRO and inexact simulation techniques within its framework. The modeling system specializes in (i) accounting for physical nutrient transport mechanisms, as well as characterizing the spatiotemporal heterogeneity of system components, (ii) handling uncertainties expressed as interval values, probability density functions (PDFs), and fuzzy sets, as well as dealing with the variability of the second-stage cost that