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Risk minimization in water quality control problems of a river system

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Abstract

Methodologies are presented for minimization of risk in a river water quality management problem. A risk minimization model is developed to minimize the risk of low water quality along a river in the face of conflict among various stake holders. The model consists of three parts: a water quality simulation model, a risk evaluation model with uncertainty analysis and an optimization model. Sensitivity analysis, First Order Reliability Analysis (FORA) and Monte–Carlo simulations are performed to evaluate the fuzzy risk of low water quality. Fuzzy multiobjective programming is used to formulate the multiobjective model. Probabilistic Global Search Laussane (PGSL), a global search algorithm developed recently, is used for solving the resulting non-linear optimization problem. The algorithm is based on the assumption that better sets of points are more likely to be found in the neighborhood of good sets of points, therefore intensifying the search in the regions that contain good solutions. Another model is developed for risk minimization, which deals with only the moments of the generated probability density functions of the water quality indicators. Suitable skewness values of water quality indicators, which lead to low fuzzy risk are identified. Results of the models are compared with the results of a deterministic fuzzy waste load allocation model (FWLAM), when methodologies are applied to the case study of Tunga–Bhadra river system in southern India, with a steady state BOD–DO model. The fractional removal levels resulting from the risk minimization model are slightly higher, but result in a significant reduction in risk of low water quality.

Keywords: Fuzzy sets; Optimization models; Uncertainty analysis; Waste management; Water quality

1. Introduction

Waste load allocation (WLA) in streams refers to the determination of required pollutant treatment levels at a set of point sources of pollution to ensure that an acceptable level of water quality is maintained throughout the stream. Waste load allocation problems are characterized by uncertainties due to both randomness and imprecision. Uncertainty due to randomness arises mainly due to the random nature of the input variables of water quality simulation model and that due to imprecision or fuzziness is associated with setting up the water quality standards and goals of Pollution Control Agencies (PCA), and the dischargers. Applications of fuzzy sets in addressing uncertainty due to imprecision in water resources problems may be found in Bender and Simonovic [2] and Teegavarapu and Simonovic [27].

Some early works related to the optimal Waste Load Allocation (WLA) problems are due to Liebman and Lynn [10] and Loucks et al. [12]. The WLA problem was formulated as a single objective optimization problem by them. Burn and McBean [5,6] presented a stochastic optimization model in which the concern

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was with the interaction between BOD and DO concentration in the river. Fujiwara et al. [8,9] developed a recursive procedure to express the dissolved oxygen concentration at a water quality checkpoint in a river system in terms of the fractional removal levels of the pollutants discharged to the river system. Takyi and Lence [24] proposed a Markov chain model for seasonal water quality management of a river system. Chebyshev criterion was used by Takyi and Lence [25] to develop direct regulation of a water quality management model that maximized excess water quality above the water quality goal at all checkpoints along the river. The Multiple Realization Model (MULTREA) proposed by Takyi and Lence [26], uses both simulation and optimization to address uncertainty in a WLA model.

Multiobjective problem solving technique was introduced by Monarchi et al. [14], which allowed the decision maker to trade off one objective versus another in an interactive manner. Tung and Hathhorn [28] reveal that fuzzy optimization is a valuable tool for solving the multiobjective water quality management problems. Wen and Lee [29] presented a multiobjective optimization approach based on neural networks for water quality management in a river basin. Sasikumar and Mujumdar [19] have formulated fuzzy waste load allocation model (FWLAM) to demonstrate the application of fuzzy decision making in a water quality management of a river system. Mujumdar and Subbarao [16] used genetic algorithm to solve FWLAM using the water quality simulation model QUAL2E, developed by the US Environmental Protection Agency.

A methodology for evaluating the fuzzy risk of low water quality is presented by Subbarao et al. [21]. First Order Reliability Analysis (FORA) and Monte–Carlo Simulations (MCS) were applied to compute the fuzzy risk. Starting with that methodology two models are developed in this paper to minimize the fuzzy risk of low water quality: (i) risk minimization model and (ii) Modified fuzzy waste load allocation model. The risk minimization model consists of three component models: (i) water quality simulation model; (ii) fuzzy risk evaluation model and (iii) optimization model to minimize the risk. The water quality simulation model is a simple one-dimensional BOD–DO model and is solved by the backward finite difference method. In the modified fuzzy waste load allocation, the FWLAM is modified accounting for skewness of the water quality indicator DO. Here base values are not considered in the optimization model; only the moments (i.e. mean, variance and skewness) of water quality indicator are used. Resulting non-linear optimization problems of both the models are solved by Probabilistic Global Search Lausanne (PGSL), a direct stochastic algorithm for global search developed by Raphael and Smith [18]. Tests on the benchmark problem having multi-parameter non-linear objective function have revealed that PGSL performs better than genetic algorithm and advanced algorithms for simulated annealing [17].

2. Risk minimization model

Uncertainties due to both randomness and imprecision in a water quality management problem are considered in developing the risk minimization model. Water quality at a location in a stream depends on the variability of a number of input parameters (e.g. temperature, streamflow, upstream water quality etc.). In FWLAM developed earlier, such variability is not considered, as it is a deterministic model. Risk minimization model, developed in this paper, has two parts: deterministic and stochastic. The deterministic part maximizes the minimum acceptability level of FWLAM for mean condition of the input parameters. The stochastic part minimizes the fuzzy risk of low water quality, incorporating both types of uncertainties in the optimization model. For ease in understanding the risk minimization model, a brief overview of FWLAM is first presented in the following Section 2.1.

2.1. FWLAM

The fuzzy waste load allocation model (FWLAM) developed by Sasikumar and Mujumdar [19] forms the basis for the optimization models developed in this paper. The FWLAM is described using a general river system. The river consists of a set of dischargers that are allowed to release pollutants into the river after removing some fraction of the pollutants. These fractional removal levels of the pollutants are necessary to maintain the acceptable water quality condition in the river as prescribed by the Pollution Control Agency (PCA). The acceptable water quality condition is ensured by checking the water quality in terms of water quality indicator levels (e.g., DO concentration) at a finite number of locations which are referred to as checkpoints. In a water quality management model, the concentration level of the water quality indicator at a checkpoint is expressed as a function of the fractional removal levels for the pollutants released by the dischargers upstream of that checkpoint in the river system. An optimization problem is formulated with the set of fractional removal levels and the minimum acceptability level forming the decision variables. The goal of the PCA is to improve the water quality and that of the dischargers is to minimize the fractional removal levels and they are in conflict with each other. These goals are treated as fuzzy goals and modeled using appropriate fuzzy membership functions. In the FWLAM, the following fuzzy optimization problem is formulated to take into account the fuzzy goals of the PCA and dischargers.