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A stochastic conflict resolution model for water quality management in reservoir–river systems

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Abstract

In this paper, optimal operating rules for water quality management in reservoir–river systems are developed using a methodology combining a water quality simulation model and a stochastic GA-based conflict resolution technique. As different decision-makers and stakeholders are involved in the water quality management in reservoir–river systems, a new stochastic form of the Nash bargaining theory is used to resolve the existing conflict of interests related to water supply to different demands, allocated water quality and waste load allocation in downstream river. The expected value of the Nash product is considered as the objective function of the model which can incorporate the inherent uncertainty of reservoir inflow. A water quality simulation model is also developed to simulate the thermal stratification cycle in the reservoir, the quality of releases from different outlets as well as the temporal and spatial variation of the pollutants in the downstream river. In this study, a Varying Chromosome Length Genetic Algorithm (VLGA), which has computational advantages comparing to other alternative models, is used. VLGA provides a good initial solution for Simple Genetic Algorithms and comparing to Stochastic Dynamic Programming (SDP) reduces the number of state transitions checked in each stage. The proposed model, which is called Stochastic Varying Chromosome Length Genetic Algorithm with water Quality constraints (SVLGAQ), is applied to the Ghomrud Reservoir–River system in the central part of Iran. The results show, the proposed model for reservoir operation and waste load allocation can reduce the salinity of the allocated water demands as well as the salinity build-up in the reservoir.
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1. Introduction

Increasing demand for water, higher standards of living, depletion of resources of acceptable quality, and excessive water pollution due to agricultural and industrial expansions have caused intensive social and environmental predicaments all over the world. The previous works related to the water quality management in reservoir–river systems can be classified into three categories: reservoir operation considering the water quality issues, waste load allocation in the river systems and the water quality management in river–reservoir systems. In the following sections, some background information and recent works related to the above mentioned categories are presented.

During the past decades, there have been many advances in reservoir operation. Karamouz and Vasiliadis [24], Mousavi et al. [31], and Labadie [27] have made a thorough review of previous studies in this field. Review of the previous works show that there have been less studies focusing on the reservoir operation considering the water quality issues.

Fontane et al. [14] linked the WESTEX water quality simulation model with a dynamic programming model to develop optimal policies for a multi-outlet selective withdrawal structure. Their model only considered the water temperature as the water quality indicator due to computational difficulties.

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Loftis et al. [29] developed a non-linear optimization model to satisfy quantity and quality requirements in a multiple reservoir system. They separated quantity and quality aspects of the problem into distinct sub-problems and optimal operating policies achieved through iterative, successive solution of the sub-problems.

Dandy and Crawley [8] developed water quantity and quality operational polices for the head works of the city of Adelaide, Australia. In their paper, the reservoir is considered to be completely mixed and an existing linear programming model for operation of the system is modified to identify policies which minimize total system costs and improve the average salinity of the supplied water.

Nandalal and Bogardi [32] developed a simple non-linear optimization model to operate a reservoir for improving the quality of water supplied. In this model, the optimal release from each outlet is calculated for a total release obtained from a classical Stochastic Dynamic Programming (SDP) model.

Chaves et al. [7] used optimization and artificial intelligence techniques for reservoir operation considering the water quality issues. In their work, water quality simulation is carried out using a simple artificial neural network model. They used a fuzzy stochastic dynamic programming model for calculating the optimal reservoir operation policies, but selective water withdrawal is not considered in this optimization model.

Optimal waste-load allocation in river systems has been given considerable attention in literature. Traditional waste-load allocation models have been formulated to minimize the total effluent treatment cost while satisfying water quality standards throughout the river system. In the recent efforts (such as those developed by Ellis [11], Burn [3], Fujiwara et al. [15]) some sources of uncertainty such as decay and reaeration rates have been explicitly considered. In these works, the chance constraint method is usually used to develop a stochastic waste load allocation model for a low flow condition.

The economic efficiency of the seasonal waste-load allocation models has been demonstrated by Boner and Furland [1], Ferrara and Dimino [13], Lence and Takyi [28], and Takyi and Lence [38]. Because of the computational problems of the seasonal waste load allocation due to large number of decision variables, in all previous works, different scenarios have been developed to approximate the seasonal treatment levels. Kerachian and Karamouz [25] proposed a GA based multi-objectives waste load allocation model which can consider the temporal variations of climatic and hydrologic condition of the system and the qualitative and quantitative characteristics of the point loads. In their model, deterministic waste load allocation rules are determined for the Karoon River in Iran.

Previous researches for developing water quality management policies in river–reservoir systems are also limited. De Azvedo et al. [9] presented an integration of surface water quantity and quality objectives within the framework of a decision-support tool in an application to the 12,400-km^2 Piracicaba River Basin in the state of Sao Paulo, Brazil. Emphasis was given to simulation-based assessment of strategic planning alternatives through the combined use of water allocation (MODSIM) and water quality routing (QUAL2E-UNCAS) models.

Sharon et al. [5] evaluated several water management scenarios for a portion of the mainstream Klamath River in the USA using computer models of water quantity (MODSIM) and quality (HEC-5Q). These models were used to explore the potential for changing system operations to improve summer/fall water quality conditions to benefit declining fishes. By comparing and contrasting several model simulation results, some operational strategies that could improve water quality were determined.

This paper presents a conflict resolution approach for the development of combined optimal reservoir operating and monthly waste load allocating rules to improve the quality of supplied water. In order to include a conflict resolution scheme, the Nash bargaining theory [33] is used in the proposed methodology. In this paper, the expected value of the Nash product is considered as the objective function of the model, where a coupled optimization/conflict resolution approach is developed considering the water quality issues.

To reduce the computational burden of the classical GAs, a new approach namely Varying Chromosome Length Genetic Algorithm (VLGA) is used. Kerachian and Karamouz [25] proposed a dynamic chromosome length genetic algorithm for developing deterministic waste load allocation policies in river systems. In this paper, that idea is modified to be applicable for deriving optimal stochastic operating rules for reservoir–river systems. The efficiency of the model is evaluated using the available water quantity and quality data of the Ghomrud Reservoir–River system, central Iran.

Simulation of the developed monthly reservoir operating and waste load allocation rules shows that the application of these rules reduces the TDS concentration in the allocated water as well as the salinity build-up in the reservoir.

In the next sections, the conflict resolution algorithm is discussed followed by a stochastic optimization model. Then the formulation of the water quality simulation model in reservoir and downstream river is presented. Finally, the solution of the proposed model by VLGA and a case study are discussed.

2. Conflict resolution algorithm

Conflict resolution methodology has been applied to limited cases in the field of water resources engineering and management. Richards and Singh [36] proposed a two-level game for water allocation to different demands. They derived several propositions on the consequences of different bargaining rules for water allocation. Shahidehpour et al. [37] applied the Nash conflict resolution approach to a power generation problem.

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