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Probabilistic reservoir operation using Bayesian stochastic model and support vector machine

Mohammad Karamouz [a,b,*], Azadeh Ahmadi [a,c], Ali Moridi [d]

[a] School of Civil Engineering, University of Tehran, Tehran, Iran
[b] Polytechnic Institute of NYU, Brooklyn, NY, United States
[c] Department of Civil Engineering, Isfahan University of Technology, Isfahan, Iran
[d] Water Engineering Research Institute, Tarbiat Modares University, Tehran, Iran

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ABSTRACT

Available water resources are often not sufficient or too polluted to satisfy the needs of all water users. Therefore, allocating water to meet water demands with better quality is a major challenge in reservoir operation. In this paper, a methodology to develop operating strategies for water release from a reservoir with acceptable quality and quantity is presented. The proposed model includes a genetic algorithm (GA)-based optimization model linked with a reservoir water quality simulation model. The objective function of the optimization model is based on the Nash bargaining theory to maximize the reliability of supplying the downstream demands with acceptable quality, maintaining a high reservoir storage level, and preventing quality degradation of the reservoir. In order to reduce the run time of the GA-based optimization model, the main optimization model is divided into a stochastic and a deterministic optimization model for reservoir operation considering water quality issues.

The operating policies resulted from the reservoir operation model with the water quantity objective are used to determine the released water ranges (permissible lower and upper bounds of release policies) during the planning horizon. Then, certain values of release and the optimal releases from each reservoir outlet are determined utilizing the optimization model with water quality objectives. The support vector machine (SVM) model is used to generate the operating rules for the selective withdrawal from the reservoir for real-time operation. The results show that the SVM model can be effectively used in determining water release from the reservoir. Finally, the copula function was used to estimate the joint probability of supplying the water demand with desirable quality as an evaluation index of the system reliability. The proposed method was applied to the Satarkhan reservoir in the north-western part of Iran. The results of the proposed models are compared with the alternative models. The results show that the proposed models could be used as effective tools in reservoir operation.

1. Introduction

Reservoir operation should be done in the context of the principle of integrated water resources management (IWRM) considering both quality and quantity issues. Within a holistic framework, the reservoir operating strategies should aim to improve the efficiency of water utilization and prevent eutrophication and degradation of the reservoir.

The present work focuses on developing a framework that reconciles water quantity and quality objectives for drawing long-term reservoir operation policies. Other aspects of IWRM such as social, environmental and economic are considered in the continuation of this study. Some of these issues are implicitly considered when the proposed models allocate water to meet the downstream demands including instream requirements. The social and economical welfare of the region are highly dependent upon the planning schemes to operate the reservoir as the only dependable water resources. Development of operating policies for real-time operation of a reservoir is one of the main outcomes of this study to solve the conflicts on water usage while improving the quality of water released and water stored in the reservoir.

Several investigators have emphasized the need to jointly consider water quality and quantity issues for integrated water resources management [1,4,28].

Previous studies for optimal reservoir operation with water quality objectives have typically adopted linear programming techniques to include, for example, dissolved oxygen and biochemical oxygen demand control [20] or reliability programming (chance-constraint) for salinity control [22].

* Corresponding author. Address: School of Civil Engineering, University of Tehran, Tehran, Iran. Tel.: +98 2188555854; fax: +98 2188701507.
E-mail addresses: mkaramou@poly.edu, karamouz@ut.ac.ir (M. Karamouz), azadehahmadi@ut.ac.ir (A. Ahmadi), moridi@cic.aut.ac.ir (A. Moridi).

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Loftis et al. [19] developed a methodology combining a non-linear optimization model and a water quality simulation model to satisfy water quantity and quality requirements in a multi-reservoir system. In order to reduce the computational difficulties of their methodology, they assumed that the reservoir water qualities in different years are independent from. Dandy and Crawley [7] modeled the operation of a multiple reservoir system with linear programming model to identify policies which minimize total system costs. Mehrez et al. [21] focused on real-time operations for service to agricultural and urban water users. An optimization model was used to allocate water in the distribution system from a variety of sources to meet water quality requirements of the influent at a minimal cost. Hayes et al. [12] developed optimal daily reservoir release policies which resulted in a water quantity/quality model to maximize hydropower revenues, subject to various flow, headwater and water quality constraints. Azevedo et al. [2] assessed the strategic planning alternatives through the combined use of water allocation and water quality models, within a DSS framework.

Looking at the variety of related studies in the literature, less attention has been given to water quality aspects of reservoir operation. Furthermore, selective withdrawal considering the intrinsic and forecast uncertainties of inflow to the reservoir are missing from most planning and operation models developed in the past. In this study, attempts have been made to address this major challenge in reservoir operation. Therefore, a water quality simulation model and an optimization model are linked to generate operating policies for real time operation considering the uncertainties of inflow to the reservoir. The optimization problems with computational complexity due to a high number of decision variables and non-linear behavior can be solved with the use of the genetic algorithm (GA) method.

In the last decade, more attention has been given to evolutionary algorithms (EA) in general and specifically to genetic algorithms (GA). Genetic algorithms are search algorithms based on the mechanism of natural gene selection and natural genetics. It originated in the mid 1970s [13] and emerged as a powerful optimization approach. An excellent introduction to GA is given by Goldberg [9], and several other investigators have summarized the essentials of genetic algorithm modeling. Dorn and Ranjithan [8] used a two objective genetic optimization algorithm (NSGA-II) and a one-dimensional stream channel, fate and transport water quality model. Chaves and Kojiri [5] applied a stochastic fuzzy neural network (SFNN), trained by a genetic algorithm (GA), to optimize of the monthly operational strategies considering maximum water utilization and improvements on water quality simultaneously. Kerachian and Karamouz [17,18] proposed GA-based models for water quality management in reservoirs and river–reservoir systems. They used the Nash bargaining theory in order to include conflicting interests of different decision makers and stakeholders of the system. Shirangi et al. [24] developed an algorithm combining a multi-objective genetic algorithm based optimization model and a water quality simulation model for determining a trade-off curve between objectives related to the allocated water quantity and quality. They extended the work by Kerachian and Karamouz [17,18] by decomposing the main optimization problem to a long-term and several annual optimization models. They assumed that the reservoir water qualities in different years are independent from.

In this paper, the reservoir operation model proposed by Kerachian and Karamouz [17,18] is considered and in order to reduce the run time of the model, the main optimization problem is decomposed to a stochastic optimization model with the water quantity objective and a long-term optimization model with the water quality objective. The Bayesian stochastic genetic algorithm (BSGA) model incorporates the intrinsic and forecast uncertainties of inflow to the reservoir and provides the operating rule used to simulate the optimal reservoir release ranges for each month. These optimal ranges are considered as constraints for the long-term reservoir operation optimization model. This way, the model with the water quality objective gets feedback from the model with the water quantity objective and there is no need to assume that the reservoir water qualities in different years are independent from. In addition to the quality of the water released, the quality of water stored in the reservoir is considered as the stakeholders' player in the second reservoir operation model. Also the shortcoming of previous works by Kerachian and Karamouz [17,18] in developing operating policies with respect to water quality conditions in the reservoir has been realized while using the support vector machine (SVM) model. The application of SVM for development of operating policies is also new and applicable.

The difference between the present work and the work of Shirangi et al. [24] is the way the optimization algorithm is decomposed. They used a long-term deterministic model to find the reservoir storages at the beginning and the end of each water year. They used a water quality model to check the monthly releases to satisfy demand and water quality requirement. In this paper, a stochastic model is used to determine the ranges of monthly releases that will be constraints in the long-term water quality model. In this way, quality requirements are observed throughout the study horizon instead of one year at a time that Shirangi et al. [24] utilized. The other difference between the two studies is the use of SVM versus ANFIS when driving the operating rules.

The fundamental of support vector machines (SVM) was developed by Vapnik [30], based on the structural risk minimization principle from statistical learning theory and gained popularity due to its many interesting features and promising empirical performance. The application of SVM has received attention in the field of hydrological engineering. Choy and Chan [6] used support vectors of the SVM to determine objectively the structure of the radial basis function networks. They applied such networks in modeling the relationship between rainfall and river discharge. Yu et al. [32] proposed a scheme that combined chaos theory and SVM to forecast the daily runoff. Bray and Han [3] applied SVM to forecast runoff, focusing on the identification of an appropriate model structure and relevant parameters. Sivapragasam and Liong [25] used support vector machine models to improve the forecasting of streamflow for different flow categorization.

The main purpose of this study is to develop the reservoir operating policies considering water quality and quantity issues, in a way that ensures water with better quality is allocated to water demands. The considered objectives are including supplying the demand downstream of the reservoir with acceptable water quality, maintaining the carrying capacity of the reservoir, and preventing the degradation of the reservoir. The water quality and quantity objective functions are defined using the Nash bargaining theory. Considering computational complexity of the problem and non-linear behavior of the objective function, in this study, GA is used to solve the optimization models. The operating policies are generated to incorporate the intrinsic and forecast uncertainties of inflow to the reservoir using Bayesian decision theory. Considering the water quality objective, the reservoir system could be operated so that water with better quality is allocated to water demands. Therefore, first optimal release ranges are determined considering quantity concerns and then certain releases are obtained from the model with quality objective functions. In this model, selective withdrawal schemes are developed to improve water quality in the reservoir and water yield using a linked water quality simulation model with the optimization model to estimate the effects of selective withdrawal on the quality of water stored in and water released from the reservoir.