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# Optimal operation of multipurpose reservoirs using flexible stochastic dynamic programming

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**Abstract**

This paper presents a fuzzy stochastic dynamic programming (FSDP) approach to derive steady-state multipurpose reservoir operating policies. The vagueness associated with some operating objectives as well as with the decision-making process is apprehended through fuzzy set theory. Operating objectives are considered as fuzzy sets and their membership functions represent decision maker's preferences and satisfaction associated with particular states of the system. At each stage of the FSDP algorithm, current operating objectives are considered as flexible constraints while the fuzzy goal is obtained from the set of maximizing decisions calculated at the previous stage. The decision function results from the aggregation of the flexible constraints and the fuzzy goal. Continuous re-optimization models, with discrete FSDP-derived membership functions approximated by cubic splines, are used for implementing FSDP-derived results in real-time or simulated operation. The model can also employ different hydrologic state variables to describe the temporal persistence of the streamflow process. The proposed approach is implemented to derive operating policies for the Mansour Eddahbi reservoir (Morocco) with current inflow as the hydrologic state variable.



*Keywords:* Reservoir operation; Fuzzy mathematical programming; Multiobjective decision problems

## 1. Introduction

Long-term optimal management of multipurpose reservoirs is a sequential, stochastic and often fuzzy optimization problem. Sequential decisions have to be taken so that time-dependent and imprecise demands can be fulfilled under constraints imposed by the economical and physical limitations of the system, as well as by the stochastic nature of inflows. As pointed out by Yeh [1], there is no general method for optimizing reservoir operation; it ranges from simulation to optimization models. If early studies focused on hydropower reservoirs, a recent shift has been observed toward multipurpose systems. This movement can be explained by the raising concerns about environmental quality and by our ability to cope with evolving objectives in the management of water resources systems (Loucks [2]). The multiobjectivity issue becomes even more complex when some of the objectives are difficult-to-quantify, i.e. they cannot or should not be converted to monetary units. For example, such objectives can be environmental quality, recreation, flood control, subsistence agriculture in developing countries. To deal with this issue, traditional operation

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models based on economic objectives must be adapted so that the inherent vagueness can be captured in the definition of the loss (or penalty) functions (Teegavarapu and Simonovic [3]). An alternative to this approach consists in eliciting decision makers' satisfaction associated with particular states of the system and then to integrate it into an optimization model (Fontane et al. [4]). This paper presents a general optimization approach for deriving efficient reservoir operating rules while considering: (1) the operating objectives as flexible constraints, (2) the temporal persistence of the hydrologic conditions, and (3) the unboundedness of the planning period. The flexibility of the constraints allows us to capture decision makers' preferences on the solution and to relax the set of possible solutions so that partially feasible solutions can also be examined.

Stochastic dynamic programming (SDP) is a powerful technique for optimizing reservoir operation problems in which the stochastic nature of the inflows plays a key role and has a deep impact on system performance. In the implicit SDP formulation, many sequences of streamflows are used as inputs to deterministic DP models with well-defined termination time. Then, the optimal policies are traditionally determined by regression analysis. In the explicit SDP formulation, the temporal persistence of the streamflow process is directly incorporated in the optimization algorithm by means of transition probabilities. This second alternative better exploits the information found in most hydrologic time series, but it is also more computationally demanding since it requires an additional state variable (the hydrologic state variable). Recent applications of SDP can be found in Tejada-Guibert et al. [5,6], Liang et al. [7], Kim and Palmer [8].

Like other optimization techniques, SDP can be fuzzified so as to capture the imprecise nature of the constraints and/or the objectives. Fuzzy set theory and fuzzy logic provide mathematical frameworks for dealing with vague objects and approximate reasoning. There are basically two ways to implement those concepts in reservoir operation problems. The first utilizes a fuzzy-rule based scheme to derive operating rules using an "IF-THEN" principle to emulate reservoir operators' knowledge (Shrestha et al. [9]). The second relies on fuzzified traditional optimization techniques such as linear programming (LP) and dynamic programming (DP). Teegavarapu and Simonovic [3] optimize short-term reservoir operation by minimizing economic losses with LP and non-LP formulations in which both the penalty coefficients and zones are considered fuzzy. Fontane et al. [4] use a deterministic fuzzy DP (FDP) algorithm to determine optimal monthly release decisions based on Bellman and Zadeh's framework [10]. This process is repeated a large number of times using synthetically generated equally likely streamflows so that the release rule can be obtained from regression analyses. This approach presents some interesting features but also has some limitations. For example, it implicitly assumes that current decisions are independent of future events and decisions beyond the planning horizon. So, the distant future is ignored. The maximal solutions are supplied by the max–min formulation, which only depends on the most pessimistic objective. Due to the nature of DP, this lack of compensation deeply affects the overall sequence of decisions; one unambitious objective is enough to make a trajectory uninteresting. In addition, the implementation of FDP-derived results is very sensitive to the hydrological regime, so that the effectiveness of the release rule can easily become questionable because of the low coefficients of determination for the regressions. Finally, the implementation of an FDP approach in a Monte Carlo simulation framework only considers the stochastic variability of the hydrologic inputs, ignoring the temporal persistence found in most hydrologic time series. The proposed FSDP model addresses these issues.

In the present study, operating objectives are considered as flexible constraints of a stochastic optimization problem over an unbounded planning horizon. The recursive fuzzy DP equation is thus generalized by (1) directly incorporating the probability distributions of the hydrologic inputs, (2) explicitly considering the unboundedness of the planning horizon, (3) modeling multiobjective decision-making by allowing compensatory connectives. Consequently, the reservoir operation problem is analyzed as a never-ending sequence of decisions, in which current and future decisions may influence each other. In this paper, the objectives faced by the decision maker are the immediate and the future consequences associated with a release decision. The immediate consequences are the degrees indicating how well the various current operating objectives are satisfied. The future consequences,