17 WATER RESERVOIR APPLICATIONS OF MARKOV DECISION PROCESSES

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Abstract: Decision problems in water resources management are usually stochastic, dynamic and multidimensional. MDP models have been used since the early fifties for the planning and operation of reservoir systems because the natural water inflows can be modeled using Markovian stochastic processes and the transition equations of mass conservation for the reservoir storages are akin to those found in inventory theory. However, the "curse of dimensionality" has been a major obstacle to the numerical solution of MDP models for systems with several reservoirs. Also, the use of optimization models for the operation of multipurpose reservoir systems is not so widespread, due to the need for negotiations between different users, with dam operators often relying on operating rules obtained by simulation models.

In this chapter, we present the basic concepts of reservoir management and we give a brief survey of stochastic inflow models based on statistical hydrology. We also present a stochastic dynamic programming model for the planning and operation of a system of hydroelectric reservoirs, and we discuss some applications and computational issues. We feel many research opportunities exist both in the enhancement of computational methods and in the modeling of reservoir applications.

17.1 INTRODUCTION

Dams and reservoirs have long been used for storing surplus water during rainy seasons to provide irrigation and drinking water during dry periods. They prevent flooding during periods of thaw or unusually high rainfall. They also serve to regulate flow and depth of water in lakes and rivers for navigational purposes, and to move ships up and down locks as in the Panama canal and the Saint-Lawrence seaway. Throughout the twentieth century, hydroelectric production has become a major economic benefit of dams, reservoirs and water resources.

The sequential nature of the reservoir management decisions, together with the inherent randomness of natural water inflows, explains the frequent modeling of reservoir management problems as Markov decision processes (MDPs), and their optimization by stochastic dynamic programming (SDP). The first discussion of reservoir management in this framework is usually credited to Pierre Massé [29] in 1946. Optimization results for the hydroelectric production of a single reservoir were published a decade later, with the numerical computation of an optimal policy [25] and the analytic structure of optimal policies for hydrothermal systems [12]. These results paralleled similar developments that occurred in inventory theory at the same epoch. There is an extensive literature on models and methods for reservoir optimization. Surveys can be found in [22, 53, 54].

Nonetheless, large reservoir systems have been in operation for decades before the development of optimization models. Reservoir operators have thus relied on rule curves and other agreed upon operating rules, as well as their own judgment and experience in making reservoir release decisions [27]. While optimization models are now often used in practice for planning purposes, their use in real-time multiple-reservoir operation is not so widespread. According to [32],

> "The need for comprehensive negotiations and subsequent agreements on how to operate a reservoir system seems to be a main reason why most reservoir systems are still managed based on fixed predefined rules. [. . .] Optimization models can help define these predefined rules, rules that satisfy various constraints on system operation while minimizing future spills or maximizing energy production or minimizing expected future undesired deviations from various water release, storage volume and/or energy production targets."

The "optimization models" referred to in the above citation are usually based on linear programming (LP) or nonlinear programming (NLP), with the random variables of future inflows replaced by their most recent forecasts. These (deterministic) models must be solved every period with updated forecasts and their solutions provide an *open loop control*. By contrast, an optimal policy of an MDP gives a *closed loop control*, or *feedback solution*, which is more in the form of traditional operating rules.

On the other hand, for reservoir systems whose main purpose is hydroelectric generation, the use of solutions from optimization models is widespread. In [45, 49], for instance, MDP models are presented for the long term planning of the aggregated system, to obtain optimal policies for monthly release and storage targets. Then a hierarchy of deterministic models [13] are used for medium term (NLP) and short term scheduling (LP). See also [16]. A comparison of optimal MDP solutions with traditional rule curves solutions was made in [45] for the Brazilian system, where optimal MDP solutions were shown to have the same reliability as rule curve solutions, but with significantly increased profits.

Stochastic optimization models of hydroelectric production are usually needed when the planning horizon has a length of one or several years, with a time step of one month or longer. The long term scheduling of hydroelectric production is mainly concerned with the larger (annual or multiannual) reservoirs managed by a utility. Typical problems consider twenty or more such reservoirs and are therefore multidimensional. In general, an optimal decision rule for a given period would thus consist of twenty functions of at least twenty variables, each function giving a release target for one reservoir depending on the stored volumes at every reservoir in the system. Such functions are obviously impossible to tabulate numerically (curse of dimensionality). Hence research in this area has attempted to develop (1) aggregation-disaggregation methods, (2) numerical approximation and optimization methods, and (3) analytical solutions [22].

Research also addresses important modeling issues in statistical hydrology (stochastic processes of natural inflows with adequate representation of serial and spatial correlations) and energy economics (such as evaluating marginal production costs in the context of deregulated markets).

The sequel is organized as follows. A brief review of the basic reservoir management concepts and traditional operating policies, are given in §17.2. A survey of several models describing the stochastic processes of natural inflows is presented in §17.3 and a dynamic programming optimization model for a multi-reservoir hydroelectric system is given in §17.4. Different applications of MDP models are presented in §17.5. A survey of recent research on MDP solution methods is presented in §17.6. Finally, §17.7 contains directions and open problems in water reservoir applications of MDPs, and some concluding remarks.

17.2 RESERVOIR MANAGEMENT CONCEPTS

More than 5000 years ago the Egyptians measured fluctuations of the Nile river and built dams and other hydraulic structures to divert water to agricultural fields. Since then, practical water knowledge has proliferated among dam operators, farmers, and other users. But the concept of a water cycle (hydrological cycle) became firmly established in the scientific literature only in the seventeenth century [38]. The *hydrological cycle* is the continuous circulation of water from the sea to the atmosphere, then to the land and back again to the sea. The water exchanges involved at the various stages of the cycle are evaporation, water-vapor transport, condensation, precipitation, and runoff. *Runoff* from land surface is the residual water of the hydrological cycle, which has not been evaporated by plants and has not infiltrated the ground surface, so it is available for use. The collection of land whose surface waters drain into a river valley forms the *hydrographic basin* of that river.

A *dam* is a barrier built across a watercourse for impounding water. By erecting dams, humans can obstruct and control the flow of water in a basin. A *reservoir* is a (possibly artificial) lake, usually the result of a dam, where water is collected and stored in quantity for use. Reservoirs must occupy the best available sites in the hydrographic basin because their development requires unique geological, hydrological, topographical and geographical characteristics.