Environmental Modelling & Software 25 (2010) 209–222

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Combining metamodelling and stochastic dynamic programming for the design of reservoir release policies

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ARTICLE INFO

Article history:
Received 20 November 2008
Received in revised form
21 July 2009
Accepted 8 August 2009
Available online 31 August 2009

Keywords:
Integrated water resources management
Metamodelling
Distributed-parameter models
Stochastic dynamic programming
Water reservoirs management
Irrigation canals control

ABSTRACT

Increasing worldwide water withdrawal for irrigation purposes requires a more efficient management of water resources and an accurate description of irrigation water demand. This paper, with the aim of thinking 'in blue and green water terms', proposes a new approach for the design of release policies in reservoir systems serving irrigation districts. It is based on the solution of an optimal control problem, where the dynamics of the irrigation demand is modelled through a metamodel, i.e. a simple model identified on the basis of the data produced by a distributed-parameter, conceptual model. The metamodel inherits the physical description of the distributed-parameter model and, at same time, is sufficiently simple to allow the solution of the optimal control problem with stochastic dynamic programming. The proposed approach is tested on a real-world case study, the management of the Lake Como system, for which it provides satisfactory results.

1. Introduction

In the last few decades, agriculture has dramatically increased its water requirements, thus reaching 70% of total worldwide water withdrawal at the end of the last century. This figure is expected to grow even more: about 85% by the year 2030 (see FAO, 2003, and references therein). A key factor for satisfying irrigation demand is represented by water stored in reservoirs. In most cases, the regulation of such reservoirs is a very difficult task, because of the presence of multiple interests, frequently conflicting with agricultural needs. In order to prevent water losses and consequent social tensions, it is therefore necessary to know exactly the current irrigation demand when deciding daily the amount of water to be released.

The management of multi-purpose reservoir systems can be effectively tackled through the solution of a multi-objective Optimal Control Problem (OCP) which provides Pareto-efficient release policies (this topic is extensively covered in Soncini-Sessa et al. (2007) and in Castelletti et al. (2008a)). Stochastic Dynamic Programming (SDP) is by far the most adopted method for solving this kind of optimal control problem, as it can handle problems in which the system is non-linear and affected by random disturbances. Its drawback is the so-called 'curse of dimensionality', which strongly limits the number of state variables that can be used to model the water system, even when adopting the most advanced approaches, e.g. coarse grid approximation or neuro-dynamic programming (for a review of such approaches, see, for example, Castelletti et al., 2007; 2008b, and references therein).

To overcome the limitation imposed by SDP, irrigation districts are typically described with a simplified static model, namely an a priori given trajectory of the water demand. This is the water requirement of the irrigation districts when everything proceeds in a 'normal' way, including the supply of water in the past, which cannot deviate too much from its usual values. The trajectory of the demand is thus a good model when the variations in supply are small, but it is not when the variations are significant, as can be the case in drought conditions, or when a change in the status quo is planned (Castelletti and Soncini-Sessa, 2007). These two eventualities typically occur in real-world applications and the release policies so obtained are then inefficient with respect to the real demand. To improve the release policies' performance, it is therefore necessary to describe dynamically the state of the irrigation districts on the basis of which the real water demand can be computed, and to include it among the release policy arguments. This state is the water stored in the root zone of crops, which is called 'green water' (Falkenmark, 1991), as opposed to 'blue water' in lakes, rivers and groundwater stores. In other words, this

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doi:10.1016/j.envsoft.2009.08.001

basically corresponds to enlarging the blue water perspective of water management with the aim of including the green water. This approach offers the possibility of designing reservoir release policies that at the same time consider green and blue water. These are the policies that are essential for the on-demand regulation of irrigation canals, a strongly emerging issue (see Mareels et al., 2005).

To think in terms of green water is attractive, but the construction of accurate, SDP-compatible models describing its dynamics is not an easy task. On one hand, the identification of empirical lumped-parameter models is generally precluded by the absence of data: long, complete records of soil moisture measures are generally unavailable[1] (see Schiermeier, 2008). On the other hand, the definition of large, distributed-parameter, physically based and conceptual models is possible. The former are based on the numerical solution of the Richards equation to describe the water flow in the unsaturated zone (see, for example, AGNPS (Young et al., 1989) or SWAT (Arnold and Fohrer, 2005)), while the latter are instead based on a simplified description of the unsaturated zone as a cascade of few reservoirs (see, for example, SWAP (Van Dam et al., 1997) or WEC-C (Croton and Barry, 2001)). However, both are incompatible with SDP, owing to the elevated dimensions of their state. The solution is to build a simple model which is conceptual (thus avoiding identification) and characterized by few state variables (thus compatible with SDP), as proposed by Vedula and Mujumdar (1992) and Vedula and Kumar (1996). However, the absence of calibration gives rise to serious doubts on the real efficiency of the release policies designed.

We propose to overcome this limit by identifying the simple model with the data produced by simulating a distributed-parameter, physically based or conceptual model. In other words, we propose to design a simple, but accurate, model (*metamodel*) that can be effectively used for the resolution of an OCP. However, it must be pointed out that the underlying distributed-parameter model needs to be highly reliable in order that the metamodel be really effective. This cannot be presumed, but must be the result of an accurate collection of the distributed data.

Up to now, metamodelling, first introduced by Blanning (1975), has been widely applied in the formulation of design problems in mechanical and aerospace engineering (for a review see Queipo et al., 2005), but relatively few applications have appeared in the context of water resources planning, and these mainly for the optimal design of aquifer cleanup systems (Aly and Peralta, 1999) or of water distribution systems (Broad et al., 2005). Unlike in the case of these applications, here we do not consider a planning problem, but a management one; in other words, our aim is to design a reservoir release policy. Thus the purpose of the metamodel is not to permit fast simulations within a simulation–optimization scheme, but to reduce the dimensions of the state of the distributed-parameter model, so that it can be used in a dynamic optimization context. Then, on the basis of this, a practically solvable optimal control problem can be formulated. Once the release policy is obtained, its performance can be estimated by simulating the water system controlled by that policy, while representing the irrigation district with the distributed-parameter model (not with the metamodel), thus increasing the reliability of this estimate. We term *metamodelling design approach* the approach we propose of designing the policy with the metamodel and evaluating its performance with the distributed-parameter model.

We tested the potentiality offered by the metamodelling design approach on a real-world case: the management of the Lake Como system.

The paper is organized as follows. In the next section we will analyze the different forms of the policy design problem, which follow from the three possible forms of the irrigation district models: an a priori given trajectory of the water demand, a distributed-parameter model and a metamodel. Then, in order to assess the management advantages offered by the third type of model over the first one, we will consider the real-world application to the Lake Como system. Section 3 presents the application, describing the Lake Como system and its management problem. Section 4 concerns the modelling of the system, and Section 5 focuses attention on the three forms of irrigation district models. The last of these, the metamodel, is obtained by combining the a priori knowledge on the system with empirical information (provided by simulating the distributed-parameter model) into a model characterized by state-dependent parameters (Young, 1998). In Section 6 the design problems are solved and the performances compared. Before concluding with Section 9, Sections 7 and 8 describe the computational cost of the employed algorithm and the effect of the reliability of the distributed-parameter model.

2. Policy design problems

The considerations we intend to present are valid for any type of water system, but, for simplicity of exposition, we will consider the simple one represented in Fig. 1, consisting of a catchment, a reservoir and a downstream irrigation district.

We assume that the reservoir inflow[2] a_{t+1} in the time interval $[t, t+1)$, which is the outflow from the catchment, depends on the disturbance $\varepsilon_{t+1}{}^a$ that affects the catchment, which is assumed to be a white noise and is thus described by its probability distribution $\varphi^a{}_t(\cdot)$. Formally

$$a_{t+1} = f_t^a(\varepsilon_{t+1}^a)\varepsilon_{t+1}^a \sim \phi_t^a(\cdot) \tag{1a}$$

The reservoir storage s_{t+1} and its release r_{t+1} are described by

$$s_{t+1} = f_t^s(s_t, u_t, a_{t+1}) \tag{1b}$$

$$r_{t+1} = R_t(u_t, s_t, a_{t+1}) \tag{1c}$$

where u_t is the release decision[3] (*control*) at time t, belonging to the set of feasible controls $U_t(s_t)$, which is a function of the storage s_t. We assume that the functions $f^a{}_t(\cdot)$, $f^s{}_t(\cdot)$ and $R_t(\cdot)$ are periodic with period T.

A Minimum Environmental Flow (MEF) q_t^{MEF} must be left downstream from the diversion dam D, so that the flow q_{t+1} diverted to the irrigation district is given by the following *distribution policy*

[1] In order to overcome this problem, research is showing an increasing interest in the development of advanced networks of soil moisture sensors (see, for example, Wang et al., 2006, and references therein).

[2] In the symbol of a variable, the subscript denotes the time in which the variable assumes a deterministic value. For example, since the storage of a reservoir is deterministically known at time t, it is denoted by s_t. On the contrary, the inflow in the interval $[t,t+1)$ is not deterministically known at time t, since at that time it has not yet occurred and will be known only at time $t+1$. So the inflow is denoted with the symbol a_{t+1}. Before time $t+1$, for example at time t, the inflow a_{t+1} is not a deterministic variable but an uncertain one. As far as functions are concerned, their subscript denotes the time instant, or the initial instant of the time interval, to which they refer (Piccardi and Soncini-Sessa, 1991).

[3] We will speculate further on the distinction between release and release decision in Section 4.1.