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Seasonal multi-year optimal management of quantities and salinities in regional water supply systems

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ABSTRACT

A seasonal multi-year model for management of water quantities and salinities in regional water supply systems (WSS) was developed and implemented. Water is taken from sources which include aquifers, reservoirs, and desalination plants, and conveyed through a distribution system to consumers who require quantities of water under salinity constraints. The year is partitioned into seasons, and the operation is subject to technological, administrative, and environmental constraints such as water levels and salinities in the aquifers, capacities of the pumping, distribution system, and the desalination plants, and the desalination plants maximum removal ratios. The objective is to operate the system at minimum total cost. The objective function and some of the constraints are nonlinear, leading to a nonlinear optimization problem. The nonlinear optimization problem is solved efficiently by adapting (1) a set of manipulations that reduce the problem size and (2) a novel finite difference scheme for calculating the derivatives required by the optimization solver, entitled the Time-Chained-Method (TCM). The model is demonstrated on a small illustrative example and on a real sized regional water supply system in Israel.

1. Introduction

Management of water resources systems (WSS) is aided by models of various types, ranging from long-term development of large systems, to detailed operation of smaller parts such as a distribution system or an aquifer. Thus models range from highly aggregate versions of an entire water system to much more detailed models in space and time. It does not seem feasible to create a single tool that covers all levels in time and space simultaneously. The preferred option is to use a suite of models, inter-connected in a hierarchy (Shamir, 1971; Zaide, 2006). Selecting the proper aggregation in time and space for a particular application is one of the most important aspects of modeling. The short-term (weekly to annual) or long-term (years, decades) operation of a large scale WSS can be captured in a model of medium aggregation that is used to manage simultaneously, both the sources and the network (Fisher et al., 2002; Draper et al., 2003, 2004; Jenkins et al., 2004; Watkins et al., 2004). Many models deal with quantities of water to be delivered from sources to demand zones. Some models consider water quality as well, in particular salinity (Mehrez et al., 1992; Tu et al., 2005; Yates et al., 2005a,b; Zaide, 2006).

The network representation in the model can be classified according to the physical laws that are considered explicitly in the model constraints (Ostfeld and Shamir, 1993a,b; Cohen et al., 2000). According to this classification the proposed models of Tu et al. (2005), Yates et al. (2005a,b) and Zaide (2006) are flow-quality models which consider the balance of the flows and mass of quality parameters, but without explicit inclusion of the hydraulics. The inherent assumption of these models is that the hydraulic operation with the quantities prescribed by the model would be feasible hydraulically. With the inclusion of desalination plants as an important source in WSS, as is the case in Israel, water salinity consideration must be included in the management. It is important and necessary to consider both quantity and salinity in the water sources, in the water supplied to consumers and at nodes of the supply system itself. With the salinity considerations becoming an important part of management models, the complexity of the model evidently increases.

A further consideration is sustainability of the management plan. This implies meeting the needs of the present without reducing the ability of the next generation to meet its needs (Loucks, 2000). Sustainable management requires a perspective with a relatively long time-horizon, and hence the need to develop multi-year flow-quality models for WSS management. The multi-

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year models ensure that the final state of the system at the end of the operating horizon is considered, either as a constraint or having a value in the objective function.

An associated aspect of multi-year water supply management relates to hydrological uncertainty (Ajami et al., 2008), climate change (Brekke et al., 2009; Yates et al., 2005a,b), population growth (Kasprzyk et al., 2009), and the decline of water quality in the sources. The model proposed in this paper is deterministic, with a time horizon of several years, designed to minimize operating costs of an existing physical system. Uncertainty issues are addressed by sensitivity or uncertainty analysis (Lal et al., 1997; Wong and Yeh, 2002; Wu et al., 2006). Water resources management models have been solved by a variety of optimization techniques. Evolutionary Algorithms, including Genetic Algorithms and others, have gained popularity in recent years, as detailed in a recent review paper (Nicklow et al., 2010). However, as will be demonstrated below, our model is developed with structural adaptability and high computational efficiency in mind, so it can be a building-block for a model that takes uncertain considerations into account by an Ensemble or Scenario-based Optimization (Pallottino et al., 2005; Kracman et al., 2006; Mahmoud et al., 2011) or by Implicit Stochastic Optimization (Lund and Ferreira, 1996; Labadie, 2004).

This paper introduces a non-linear seasonal multi-year model for optimal management of both water quantity and salinity, which minimizes the overall cost of the system operation subject to technological, administrative, and environmental constraints. The model does not include hydraulic constraints and does not guarantee required heads at consumer nodes, yet the objective function takes into account the cost of conveyance as a function of the hydraulic properties of the network. It is implicitly assumed that the short-term hydraulic operation is feasible for the seasonal quantities prescribed by the model (Cohen et al., 2000).

1.1. Literature review

Our model differs from others in the literature in several aspects. Fisher et al. (2002) developed a model which considers the optimal water allocation from water sources to consumers through a conveyance system. It is a single-year model and includes neither quality nor hydraulic considerations.

Draper et al. (2004) developed a single time step optimization model for water allocation decisions, while the sequence of monthly time steps are linked by simulation. Water quality considerations are not included explicitly in the model, so it uses an external module which consists of an Artificial Neural Network (ANN) to estimate the water quality in the system. Thus, this model considers in some sense quality and multi-year management but not by simultaneous optimization, as we propose in this work.

Jenkins et al. (2004), Draper et al. (2003) and Watkins et al. (2004) developed and applied optimization models for multi-year management of surface and groundwater sources. The optimization problem was formulated as a linear network flow where convex economic functions are replaced by piecewise linear functions. Moreover, these models are solved only for water quantities; they do not include quality and hydraulic considerations.

Tu et al. (2005) developed a nonlinear optimization model for flow-quality operation of water distribution in regional water supply system with multi-quality sources. However, this model is not multi-year and it only considers a six month horizon with monthly time units, since the optimization problem was solved by Genetic Algorithms which is very expensive computationally.

To the best of our knowledge, the closet formulation to the proposed model is the model developed by Zaide (2006), which does not include hydraulic consideration. Zaide (2006) developed a model for multi-year combined optimal management of quantity and quality. Both quantity and salinity considerations (in the water sources, supply system and demand zones) are optimized simultaneously for a long time horizon. Since the optimization problem was solved directly without an efficient optimization plan to overcome the computational burden, the formulation had to be reduced by defining “future representative years” where the same decision variables for each “future representative year” were repeated for several years in the future. This relaxation led to a smaller optimization problem but may lead to a suboptimal solution of the original problem.

Here, we modify Zaide’s (2006) model by explicit consideration of hydraulics and then an efficient optimization plan is developed to reduce the model size without the need to of the “future representative years”. The optimization plan utilizes a new matrix representation of the quality constraints (including the dilution constraints) to extract the quality variables and reduce the optimization problem size.

To solve the optimization problem efficiently we have also developed the Time-Chained-Method (TCM), a novel and efficient scheme for calculating gradients of the objective and of the Jacobian matrix in a time-dependent inventory problem, which can be applied in other problems as well – such as groundwater management and reservoirs operation.

The details of our model and the solution technique are given in the next sections. In Section 2, the formulation of the model (objective function and the constraints) is presented. Section 3 contains the optimization plan, namely structuring the model for the optimization solver. Section 4 describes the optimization tools, including an analysis of the problem properties and how to exploit them in the optimization. Section 5 presents illustrative examples and Section 6 shows performance measures of the optimization technique.

2. Model components

In the seasonal multi-year model for management of water quantity and salinity, water is taken from sources, which include aquifers, reservoirs and desalination plants, conveyed through a distribution system to consumers who require certain quantities of water with specified salinity limits. The small WSS shown in Fig. 1 was used for model development, testing and demonstration; results will be shown (in Section 5) for the WSS shown in Figs. 4 and 5, which is a central part of the Israeli National WSS. The year is divided into seasons (two seasons in this paper, but there could be more, since the computational cost rises only linearly with the number of seasons, as detailed in Section 6 below) and the operation is subject to constraints on water levels and water quality (salinity) in the aquifers, capacities of the pumping and distribution

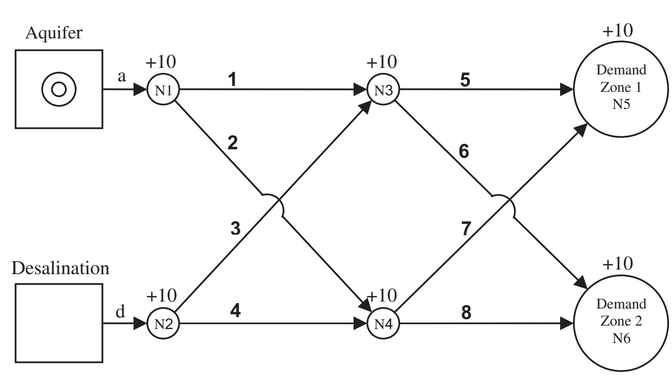

Fig. 1. Illustrative example.