Physics and Chemistry of the Earth 35 (2010) 195–203

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

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

Drought mitigation using operative indicators in complex water systems

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ARTICLE INFO

Article history:
Received 10 November 2008
Received in revised form 6 October 2009
Accepted 21 December 2009
Available online 28 December 2009

Keywords:
Droughts
Water shortage mitigation
Proactive measures
Complex water systems
Operating rules
WARGI-DSS

ABSTRACT

The definition of an effective link between drought indicators and drought mitigation measures in a regional water supply systems is a complex problem involving environmental, social and economical factors. The gap between research and practice in this field still limits the application of mathematical modelling tools more than institutional or technological features. In this paper, a methodology is developed to support the decision making process of water authorities facing droughts in complex water systems. The methodology is based on a full integration of optimization and simulation tools. The exploratory power of the optimization allows the rapid estimation of subsets of flow variables related to forecasted demands supplies and shortages that are used as operative indicators of the drought risk in future hydrological scenarios. The simulation model uses these indicators as triggers of mitigation measures in a proactive approach to drought. In the case of an overly optimistic forecast of the hydrological scenario, the proactive approach does not completely eliminate the risk of shortages. In this case, further measures have to be implemented in the water system simulation in a reactive approach to drought. These can include more expensive and higher impact measures to be taken later, after the severity of the drought event has been highlighted. In collaboration with the regional water authorities in southern Italy, the proposed methodology is currently being tested in the Agri–Sinni water system. Early applications to the Agri–Sinni water system are presented in the paper, showing the usefulness of the proposed methodology in mitigating the impacts of drought and selecting an economically efficient combination of proactive and reactive measures.

1. Introduction

In water resource systems that frequently experience severe drought events, the definition of drought mitigation measures is a central feature in the planning and management of the systems. Even though the standard approach is still to manage water emergencies rather than to prevent them using a set of measures coherently set up in a proactive approach, it appears that the legal and institutional framework is changing. Nevertheless, at this time, the practical application of mitigation measures to complex water systems is frequently limited to a nebulous, ill-defined link between these measures and drought indicators.

Characterization of complex water supply systems can require different state indicators to be used as triggers to start mitigation measures. For example, in multi-reservoir systems the reservoir storage or the total available water (reservoir storage plus inflow forecast) at the end of the wet season can be used to trigger the implementation of measures to prevent shortages during the dry season. The traditional approach to set these measures requires the use of iterative simulation models to define seasonal conditioned probability distributions of satisfying demand scenarios. The definition of this matrix of probabilities can be difficult as a large number of simulations have to be compared considering, on the one hand, potential combinations of hydrological and demand scenarios and, on the other hand, alternative management rules. In addition, normally in this approach the mitigation measures are statically associated to each scenario. When the matrix is defined, a validation phase is usually implemented by means of a further simulation of the water system.

To improve the definition of drought mitigation measures and the effective links of these measures with drought indicators, Sechi and Sulis (2007) recently developed a full integration of the simulation model WARGI-SIM (Water Resources Graphical Interface – Simulation Tool) and the linear optimization model WARGI-OPT. This mixed optimization–simulation approach was proposed with the aim of identifying and evaluating mitigation measures in a proactive approach that anticipate the trigger of mitigation actions. In fact, in order to reduce the vulnerability of the system, the proactive approach must include measures implemented before the consequences of drought event on the supply system occur. Yevjevich et al. (1978) classified drought mitigation measures into three main categories: supply-oriented measures, demand-oriented measures, and impact-minimization measures. While the impact-

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1474-7065/$ - see front matter
doi:10.1016/j.pce.2009.12.001

minimization measures are basically related to water users and various factors that can minimize their economic, environmental, and social impacts, supply- and demand-oriented measures are intended to reduce the risk relating to water shortage. The proposed mixed optimization–simulation approach aims to implement these two categories of measures (supply-oriented measures and demand-oriented measures) in a proactive approach considering a predefined infrastructural configuration of the water system.

In this paper, the mixed optimization–simulation approach is developed with application to a real system. Thanks to a collaboration with the regional water authorities within a national research project (PRIN, 2005), the approach has been undergoing testing using the Agri–Sinni (Southern Italy) water system. The Agri–Sinni is a multi-reservoir and multiuse system that has frequently experienced extreme drought events in recent decades. The preliminary results of the application of the proposed approach to this complex water system are presented in the paper.

2. Optimization and simulation approach

Since the early 1960s, simulation models have been used to model complex water resource systems. Examples of recent implementations that have specifically addressed multi-reservoir simulations and have been applied to complex water systems include, among others, AQUATOOL (Valencia Polytechnic University) (Andreu et al., 1996), MODSIM (Colorado State University) (Labadie et al., 2000), RIBASIM (DELTARES) (Delft Hydraulics, 2006), WEAP (Stockholm Environmental Institute) (SEI, 2005), and WARGI-SIM (Sechi and Sulis, 2007).

Simulation models were designed to analyze the water system behavior using complex specific algorithm rules embedded in the code (Koutsoyiannis et al., 2003). Moreover, using WARGI a mixed optimization–simulation analysis can expand the potential use of the simulation alone (Sechi and Sulis, 2007). The WARGI-SIM module defines a set of water allocation rules $[r]$ based on a set of user-defined preferences and priorities $[v]$. The user also assigns strategic reservoirs and priority levels for demands. For each strategic reservoir, a reserved volume can be assigned to high-priority demands as a function of the period of the year. When storage volume is within the reserved zone, withdraws for demands are decreased to satisfy those demands only. In such cases, based on a hierarchical list of resources and demands, additional flows could be activated to meet low-priority demands from alternative or marginal resources, or temporary restrictions could limit some of these low-priority demands.

In the mixed optimization–simulation approach, the optimization module WARGI-OPT can dynamically define a set of mitigation measures under different future hydrological scenarios. WARGI-SIM is then used to test and validate this set of measures. Particularly in the case of an overly optimistic hydrological forecast, the proactive approach does not completely eliminate the risk of drought, and additional measures must also be implemented in the simulation using a reactive approach. The reactive approach generally includes more expensive and strong impact measures to be taken later, during the drought event, without reducing the system's vulnerability to future drought events.

2.1. Proactive measures in the mixed optimization–simulation approach

In the analysis of a water system for a time horizon T with a time step t (Fig. 1), WARGI-OPT forecasts the system evolution on a time horizon Δ at each synchronization period τ_i based on the current water storages in the system's reservoirs and a user-selected future hydrological and demand scenario g. When dealing with hydrological uncertainty, the deterministic optimization method in WARGI-OPT can be implemented in an implicit stochastic environment (Hiew et al., 1989) with equally likely future hydrological scenarios. Using the approach described in Sechi and Zuddas (2008), at the synchronization period $t = \tau$, a dynamic multi-period network is generated by the optimization module replying the basic graph for each time period $\partial = 1, \Delta$ and then connecting the corresponding reservoir nodes for consecutive time periods. A dummy node representing an external-source is inserted in the multi-period network to avoid infeasibilities in the model when deficits occur. Arcs connecting the dummy node to demand nodes are also added in the multi-period network. Flows along these arcs (deficit arcs) are associated to dummy water transfers and highlight the presence of real shortages.

The water system management optimization, at the synchronization period $t = \tau$ and considering a time horizon Δ, can be written as a Linear Programming (LP) model:

$$\min_{t=(\tau,\tau+\Delta)}[c_i x_i + c_j x_j] \quad (1)$$

$$\text{s.t. } A[x_i, x_j] = b_g \quad (2)$$

$$l \leqslant [x_i, x_j] \leqslant u \quad (3)$$

In the objective function (1), the set of costs c_i represents operative, maintenance, and replace costs (OMR) or user-defined costs for transfer arcs in the multi-period network; c_j represents costs for deficit arcs and are based on demand priority ranking. The variables $[x_i, x_j]$ are the subsets of the flow variables x related to flows along the multi-period network and to flows along the deficit arcs, respectively.

As usual, constraint (2) represents continuity equations at nodes. Each node has an associated number b_g representing supply if positive, demand if negative and transhipment if equal to zero. The index g is related to the supply/demand scenario considered in the optimization.

Bounds l and u for flows $[x_i, x_j]$ in constraint (3) can be associated to capacity limits in transhipment arcs and to admissible shortages given by flows along deficit arcs.

The module WARGI-OPT gives interfaces with solvers of commercial type, as Cplex (1995), and with free solver for LP problems, as lp_solve (2008).

The exploratory power of the optimization allows for rapid estimations of the subsets of the flow variables $[x_i, x_j]$ related to forecasted demand supplies and shortages that are used as operative indicators of the drought risk in future hydrological scenarios. In fact, the simulation module WARGI-SIM uses the variables $[x_i, x_j]$ (provided by WARGI-OPT at each synchronization period τ_i) and the preferences and priorities $[v]$ (provided by the users) to set up the proactive mitigation measures $[z_\tau]$. The set up of proactive mitigation measures in the simulation can be formalized as a function involving flow variables given by optimization, priorities in demands and preferences using water sources:

$$z_\tau = f_1([x_i, x_j], v)_\tau \quad \tau = \tau_1, \tau_n \quad (4)$$

When $[x_j]_\tau \neq 0$ (implying a scenario of future shortages highlighted by the optimization phase), the set $[z]_\tau$ defines the pre-emptive actions to mitigate water scarcity impact. Pre-emptive actions belong to two main categories: supply-oriented measures, demand-oriented measures.

Starting from higher priority demands and following the hierarchical preference-list of resources, in the simulation module water transfers at the t time step are the solution of a minimum cost flow problem between resource and demand nodes in the graph representing the water system. The pre-emptive measures $[z_\tau]$ can modify the water allocations from those originally defined only using the allocation rules $[r]$ and user-defined preferences and priorities $[v]$.