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Operative indicators for drought mitigation tools in multireservoir systems

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SUMMARY – Although several studies have been done regarding drought indicators and their classification, few of these have focused on how to link operative indicators and drought mitigation measures to manage and plan complex water resource systems in an effective way. In this paper a methodology is presented and applied to the Agri-Sinni water system to aid the water Authority in the decision making process to face droughts. The methodology includes optimization and simulation tools. The optimization model uses indicators as triggers of long and short term measures in a pro-active approach. An additional set of measures could be implemented during particularly serious drought event in the simulation analysis. Results show the usefulness of the proposed approach in defining the best combination of pro-active and reactive measures.

Key words: Complex water systems, drought, pro-active measures, linear optimization, simulation, WARGI.

RESUME – *"Indicateurs opèrationnels pour l'atténuation de la sécheresse dans les systèmes à multiréservoirs". Bien que différentes études aient été menées au sujet des indicateurs de sècheresse et de leur classification, il n'y en a que peu qui se soient concentrées sur les rapports entre indicateurs opérationnels et interventions possibles pour une atténuation efficace de la sècheresse dans systèmes de ressources hydriques. Dans cet article la méthodologie suivie pour l'aide à la décision est montrée et appliquée au système Agri-Sinni. La méthodologie comprend des modèles d'optimisation et de simulation. Le modèle d'optimisation permet d'envisager une configuration des interventions possibles à court et long terme dans la stratégie proactive. Une configuration supplémentaire des interventions pourrait être appliquée pendant la sècheresse extrême. Une évaluation des effets sur le système de ressources hydriques montre une configuration des interventions qui peut être considérée comme optimale.*

Mots-clés : *Système complexe de ressources hydriques, sécheresse, interventions proactives, optimisation linéaire, simulation, WARGI.*

Introduction

Water system managers surely prefer to deal with small shortages, even if frequently repeated, more than a catastrophic shortage, dipping even into urban uses. Operating rules, which anticipate the occurrence of resource shortage implementing a proactive approach, can be searched in different ways. In multireservoir systems, water is frequently saved by applying hedging rules to stored water aiming to distribute deficits over a longer time. Draper and Lund (2004) demonstrated that the optimal hedging policy for reservoir depends on an economic balance between releases benefits and preserved water future values. Even if recently methods have been proposed for optimizing reservoirs operating rules to efficiently manage water systems in a proactive approach for droughts (Tu *et al.*, 2008), operating rules are generally determined using simulation tools in a trial-and-error approach. Operating rules suggested by "common sense" or the experience of system operators have to be tuned using simulation procedures iteratively. At each step, a set of rules is verified by simulation: operating rules are generally based on stored water to trigger water saving actions. At times the definition of operating rules might be long and difficult as a high number of potential rules have to be refined and tested.

Instead of traditional operating rules, the tool WARGI-SIM (Water Resources Graphical Interface – Simulation Tool) requires the user only to define preferences and priorities between resources and demands. Moreover, a full integration between WARGI-SIM and the optimization model WARGI-OPT has been recently developed (Sechi and Sulis, 2007). The aim of this methodology is to implement water saving actions in a proactive approach, anticipating drought events. Thanks to the adherence to real system of the multi-period network supporting the optimization model, flow configuration provided by WARGI-OPT can be seen as a reference target for the simulation model and WARGI-SIM can effectively operate to reduce the impact of water scarcity.

In Sechi and Sulis (2007) the mixed optimization-simulation approach has been presented and applied to southern Sardinia (Italy) water system. Thanks to a national research Project (PRIN, 2005) and the regional Water Authorities collaboration, the proposed methodology has been currently under test in the Agri-Sinni (Southern Italy) water system. Early applications to this complex water system are presented in the paper. The Agri-Sinni is a multireservoir and multiuse system that has frequently experienced extreme drought events in last decades. Preliminary results show the usefulness of the proposed methodology in mitigating the impacts of drought and selecting an economic efficient combination of measures in the water system management.

Optimization and simulation in drought analysis

The mixed modelling approach aims to aid water authorities in the decision making process reaching the effectiveness of the pre-emptive actions in managing droughts for a complex water resource systems. The integration in an effective way of WARGI-SIM and WARGI-OPT modules defines the best combination of measures when drought indicators reach a predefined threshold. Despite difficulties in expressing all the system operations and constraints in a mathematical form, WARGI-OPT views the entire complex water system as a single problem in time and space. This exploratory power of WARGI-OPT allows the system manager to fast estimate drought indicators under different future hydrological scenarios. The optimization model uses these indicators as triggers of measures in a pro-active approach (Sechi and Sulis, 2007). The pro-active approach includes measures implemented prior to the drought event with the aim of reducing the system vulnerability. Then, WARGI-SIM is used to test and evaluate these set of measures. Particularly in the case of too optimistic hydrological forecast, the pro-active approach does not completely eliminate the risk of drought and measures in a reactive approach have also to be implemented in the simulation. The reactive approach includes more expensive and strong impact measures to be taken later, during the drought event. The effectiveness of these temporary actions may vary with the measures already implemented in the pro-active approach.

WARGI-SIM and WARGI-OPT interactions

Time parameters in the interaction between WARGI-OPT and WARGI-SIM are the time horizon of simulation for overall system analysis (T), the time horizon of optimization (Δ), the unit simulation period ($t=1,\ T$), the unit optimization period ($\partial=1,\ \Delta$) and the period of simulation-optimization synchronization ($T = T_1,\ T_n$). Figure 1 schematizes this simulation-optimization interaction in the analysis of the water system on a time horizon of T periods.

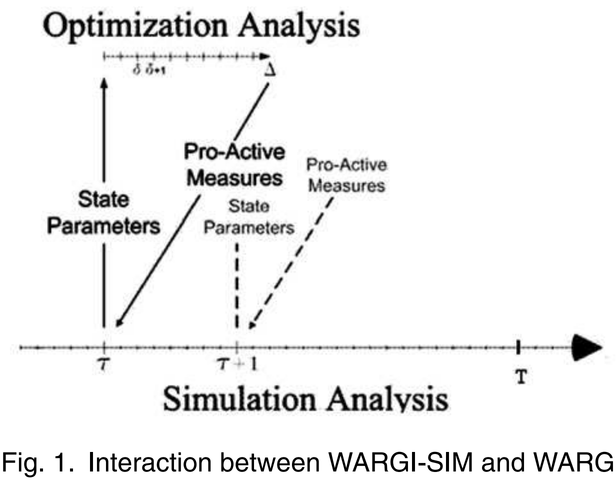

Fig. 1. Interaction between WARGI-SIM and WARGI-OPT.

At each synchronization period T_i in the simulation process, WARGI-OPT forecasts system evolution on a time horizon Δ, shorter than simulation time horizon T. Based on information provided by WARGI-OPT at each synchronization period T_i, WARGI-SIM defines a set of pre-emptive measures which can modify system management in the subsequent periods until T_{i+1}. The simulation time horizon T should be extended several decades in order to obtain a correct estimation of system performance. Optimization time horizon Δ, hydrological scenarios, and costs or penalties associated with possible deficits are key aspects in the approach proposed.

Priorities and preferences in WARGI-SIM

When pre-emptive measures do not make it possible to overcome the water scarcity in the simulation phase, WARGI-SIM introduces mitigation measures in a reactive approach. As a rule, these measures entail high economic and environmental costs for the community without reducing the system's vulnerability to future drought events. Unlike other simulation models designed to describe system behaviour using complex specific algorithm rules embedded in the code, WARGI-SIM defines reactive measures based on preferences and priorities. For each reservoir, the user can define a reserved volume as a function of the period of the year. When storage volume is within the reserved zone, downstream flows are decreased to satisfy few demands only. Strategic reservoirs and priority demands are selected by the user. In such cases, based on a hierarchical list of combination of resources and demands supply flows could be activated to meet non priority demands from alternative or marginal resources, or temporary restrictions limit some non essential uses in these demands.

The Agri-Sinni water system application

The Agri-Sinni water system is located in Basilicata, South Italy, supplying demands also in Puglia and Calabria. The main reservoirs are Monte Cotugno (capacity of $556 \cdot 10^6$ m^3) and Persusillo (capacity of $159 \cdot 10^6$ m^3) along the Sinni and Agri River respectively. Marsico Nuovo and Cogliandrino are single purpose reservoirs (irrigation and hydroelectric use) with small regulation capacity. Four intake structures (Agri, Sarmento, Sauro and Gannano) on the main rivers are used for diversion of water supplies to demands. Based on the observed monthly hydrological series at Monte Cotugno and Pertusillo over the period 1983-2005, hydrological series in the other gauging stations were generated. Hydrological series reproduce the intense water scarcities in the Agri-Sinni that occurred in the period 1989-1990 and 2001-2002. Table 1 shows main properties of hydrological series. Urban, industrial and irrigation demands are respectively $246.5 \cdot 10^6$ m^3/yr, $12.6 \cdot 10^6$ m^3/yr, and $240 \cdot 10^6$ m^3/yr.

Table 1. Statistical properties in hydrological series

Sezione	Mean ($m^3 \cdot 10^6$/year)	Stand. Dev. ($m^3 \cdot 10^6$/year)	Max ($m^3 \cdot 10^6$/year)	Min ($m^3 \cdot 10^6$/year)
Pertusillo	212.15	57.72	328.54	118.25
Monte Cotugno	277.60	106.61	494.14	118.45
Cogliandrino	89.76	32.12	147.13	33.95
Marsico Nuovo	7.82	3.04	12.91	2.53
Gannano	105.54	88.56	389.03	11.72
Agri	115.54	64.43	241.55	17.92
Sauro	50.46	25.50	101.31	11.93
Sarmento	84.10	38.79	162.06	26.42

Numerous criteria could be used to summarize system performances (Hashimoto *et al.*, 1982). Here, vulnerability (percentage value of maximum annual deficit on the total value of annual demand), time reliability (percentage value of the months in which deficit is less than predefined thresholds), volumetric reliability (percentage value of deficit on demand) have been used for preliminary estimation of system performances when a pro-active approach is implemented to face drought events.

In a first phase, before applying the mixed simulation-optimization technique, a simulation-alone analysis using the WARGI-SIM module was carried out. System simulation considered the time horizon 1983-2005 and unit time period t=1 month. Results provide an assessment of the system's capability to meet water shortage situations when a simple operating rule based on stored reservoir is implemented in the system to mitigate future drought impacts. Moreover this simulation analysis helps us assess the benefits of the pre-emptive measures defined by the mixed optimization-simulation approach. In WARGI-SIM a reserved volume was defined in Monte Cotugno and Pertusillo to assure a full-satisfaction of urban and industrial demands. The reserved volume is a monthly function defined as:

$$V_{res,t} = \sum_{j=t}^{Oct} k\left(R_{urb} + R_{ind}\right)_j \qquad j = \{Mar, Apr, May, Jun, Jul, Aug, Sep\} \tag{1}$$

The reserved volumes considered in WARGI-SIM define a management policy in the Agri-Sinni that allocates resources for civil and industrial uses and reduced releases to irrigation use. The coefficient *k* must be carefully defined to avoid unnecessary restrictions. The allocation policy requires the frequent implementation of reactive measures. Mainly, reactive measures consist of reductions in irrigation water availability by conservation actions. Water saving can be achieved by percent reduction in supply and temporary restriction limiting the irrigation of some annual crops. Results obtained by WARGI-SIM alone (Table 2) highlight the lack of effective measures in a planning strategy to increase system's reliability in the case of intensive drought. A maximum annual deficit of 80.3% and 5 years where deficit exceeds 50% determine unsustainable stress on the irrigation sector.

Table 2. Irrigation performance index values in the simulation and simulation-optimization approach

Index	SIM	OPT-SIM (A)	OPT-SIM (B)
Max annual deficit (% Demand)	80.3	67.8	40.2
Time reliability (% Years) Deficit=0%	43.5	34.8	73.9
Time reliability (% Years) Deficit ≤ 15%	65.2	56.5	95.7
Time reliability (% Years) Deficit ≤ 25%	69.6	65.2	95.7
Time reliability (% Years) Deficit ≤ 50%	78.3	87.0	100.0
Volumetric reliability (% Demand)	79.8	84.0	96.2

To mitigate the impact of these intensive drought in the predefined infrastructural configuration, water demand measures in a pro-active approach have been identified by WARGI-OPT and applied by WARGI-SIM. In a pro-active approach, water saving in the Agri-Sinni can be achieved by tiered pricing to control irrigation consumption, or efficient irrigation and losses reduction. As shown in Fig. 2, these first set of pre-emptive measures (Set A), are designed in advance of the start of drought based on information provided by WARGI-OPT and significantly reduce the maximum values of total annual deficit in the irrigation sector (-16%) and increase temporal reliability for high thresholds. A significant reduction of the reserved volume for urban and industrial demands is also presented with the coefficient *k* in (1), moving from 1 to 0.7. Moreover, the pre-emptive measures determines "programmed deficits" about which is also possible to evaluate a reduced cost for production losses in agriculture, compared to "no-programmed" deficits determined by reactive water reductions.

A second set of drought mitigation measures in the pro-active approach has been also implemented including (Set B): (i) wastewater treatment plants with a total capacity of $60 \cdot 10^6$ m^3/yr serving irrigation demands; (ii) releases from Cogliandrino serving different uses and a hydroelectric demand with high priority equaling $20 \cdot 10^6$ m^3. When these measures are coherently implemented in a planning strategy, the Agri-Sinni system's performances show a maximum annual deficit equals to 40.25% and only 1 year with annual deficit above 25%.

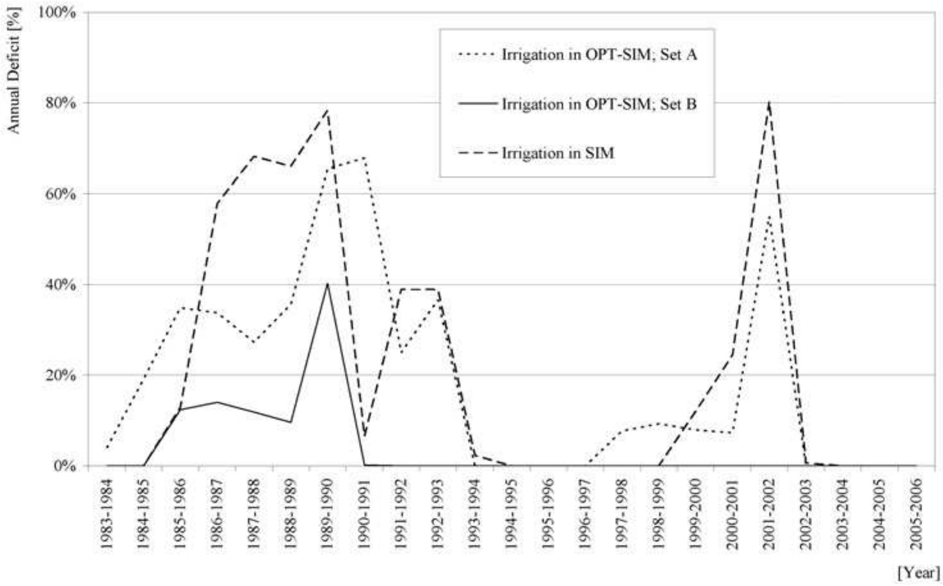

Fig. 2. Maximum annual deficit trend in irrigation sector considering different measures in pro-active and reactive approach.

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