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Developing drought triggers in complex water systems: The WARGI approach

Sechi, G. M. [1] **and A. Sulis** [1]

[1] *Department of Land Engineering, University of Cagliari, 09123 Cagliari, Italy*
Emails: sechi@unica.it, asulis@unica.it

Abstract: Drought is a creeping phenomenon, making its onset and end difficult to determine. The socioeconomic effects of drought accumulate slowly over a considerable period of time, and may linger for years after the termination of the event. Technological change is improving our ability to manage water more effectively and can facilitate the shift from crisis management approach to risk management approach. If they become part of a comprehensive early warning system, these advancements can provide decision makers with better and more timely data and information.

Particularly in water resource systems, that frequently experience severe drought events, the definition of pro-active drought mitigation measures becomes a central aspect in the systems planning and management. Decision support systems (DSS) can be used to aid water authorities to provide information and improved understanding that may eventually lead to improved system design and management.

The effectiveness of an early warning system integrated in the DSS depends on its drought indicators and triggers. The absence of a precise definition of drought indicators and triggers has led to indecision and/or inaction on the part of policy makers, water authorities, stakeholders and others. To provide an overall process and specific methodologies for the definition of drought mitigation measures and the effective linking of these measures with triggers, Sechi and Sulis (2007) recently developed a full integration of the simulation model WARGI-SIM (Water Resources Graphical Interface – Simulation Toolkit) and the linear optimization model WARGI-OPT (Optimization Toolkit).

The proposed approach has been tested in the Agri-Sinni water system (Southern Italy) within an Italian National Research Project. This paper focuses on the use of the proposed mixed optimization-simulation approach for the evaluation of the best combination of triggers and their implementation in a drought mitigation plan.

Keywords: *Droughts, Proactive Approach, Decision Support System (DSS), WARGI-DSS*

1. INTRODUCTION

Drought can be considered as one of the most complex, but least understood, of all natural disasters. It is a part of the climate variability in virtually all regions of the world, with economical, social, and environmental consequences in extended semi-arid regions.

While we cannot manage climate variability, appropriate intervention can reduce the vulnerability of complex water systems to drought. Current intervention is largely reactive and crisis driven. There is an urgent need for more risk-based management approach to drought planning. Therefore, we need to become proactive. The pro-active approach to droughts can help to:

1. Identify sectors at risk;
2. Identify stakeholders who should be involved, reducing conflicts between users and improving coordination between levels of government (organizational structure);
3. Reduce the gap in data and information and improve information dissemination;
4. Define drought mitigation measures.

Particularly in water resource systems that frequently experience severe drought events, the definition of drought mitigation measures becomes a central aspect in systems planning and management. Decision support systems (DSS) used to aid water resources authorities to provide information and improved understanding that may eventually lead to improved system design and management. They are not intended to be adequate to replace the planners and managers' judgment (Loucks, 1992) but they can assist at different levels of detail in the planning and management process.

There are a number of such generic models for simulating water resource systems: AQUATOOL (Valencia Polytechnic University) (Andreu et al., 1996), CALSIM (California Department of Water Resources and U.S. Bureau of Reclamation) (DWR, 2000), MODSIM (Colorado State University) (Labadie et al., 2000), RIBASIM (DELTARES) (Delft Hydraulics, 2006), WARGI (University of Cagliari) (Sechi and Sulis, 2007) and WEAP (Stockholm Environmental Institute) (SEI, 2005) are representative of models used for preliminary analysis of alternative plans and policies.

In our view, despite the large literature and models available, there is much more that could be added to how well and how poorly planners, managers, modelers and analysts have already done. One step ahead would be to extend the thoughts of those who described the gap between theory and practice in water resources planning and management more than a decade ago (Loucks, 1992; Simonovic 1992). This gap between what researchers in this field produce and what planners and managers find useful and use in addressing actual problems has not been closed yet.

This paper is about modeling in practice more than in theory. In particular, the emphasis is on the application of the WARGI-DSS to a complex water system located in Southern Italy that frequently experienced water scarcity conditions. The rest of the paper is organized as follow: Section 2 reviews the state of the art of integrated optimization and simulation techniques particularly related to multireservoir operations. In Section 3, an overview of the simulation and linear optimization models within the WARGI-DSS is presented. In what follows, the approaches are applied to the Agri-Sinni water system in Southern Italy for the definition and evaluation of reservoir operating rules and drought mitigation measures in a proactive approach (Section 4). Finally, some remarks on hindrances and future improvements of the proposed approach are also highlighted in Section 5.

2. OPTIMIZATION AND SIMULATION FOR COMPLEX MULTI-RESERVOIRS WATER SYSTEMS

Reservoirs regulate surface flow for allocation of water resources to meet the temporal variability of demands for multiple uses. A decision-making procedure is needed for system operation to balance demand and supply for optimal economic and social benefits. Operating rules are used to guide water managers when it is not possible to satisfy ideal storage levels and downstream releases. Ideal storage volumes in individual or multiple reservoirs are typically defined by rule curves. When conditions are not ideal, operating rules define what should be done for various combinations of system states and hydrological conditions. The purpose of operating rules is to distribute any necessary deviations from the ideal conditions in a way that minimizes the total perceived discomfort to all water users in the system.

The operating rules can be found from optimization and simulation and various models based on these methods have been proposed and reviewed by many authors (Yeh, 1985; Simonovic, 1992; Wurbs, 1993;

Labadie, 2004). In general terms, simulation methods for the analysis of water systems behaviors are often the only methods for dealing with large and complex systems that cannot be reproduced by experiment or by analytical solutions. Unfortunately, in complex systems the alternative number is quite large and the ‘trial and error’ process of simulation becomes very time consuming. The process of employing optimization to reduce the range of designs and policies requiring simulation and more in-depth evaluation is often called “preliminary screening” (Loucks and van Beek, 2005). Most of the approaches involving the combined use of optimization and simulation can be classified according to the mathematical method adopted (linear, dynamic, nonlinear, or heuristic programming), the operating rule that users can parameterize in simulation and to the kind of links between optimization and simulation modules (optimization embedded in simulation, simulation as a submodel of a main optimization model, or “optimization and simulation in parallel” are some examples).

Despite the potential use of optimization in efficient space and time exploration, full integration between simulation and optimization has not as yet been implemented with the specific aim of defining drought mitigation measures in a proactive approach. To improve the definition of drought mitigation measures and the effective linking 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 simulation-optimization approach was proposed with the aim of identifying and evaluating drought mitigation measures in a proactive approach that anticipate the trigger actions.

3. OPTIMIZATION AND SIMULATION IN WARGI-DSS

WARGI-DSS is a user-friendly tool specifically developed to help users understanding interrelationships between demands and resources for multi-reservoir water systems under water scarcity conditions, as frequently occur in the Mediterranean regions. The DSS makes it possible to take into account a large number of system components that typically characterize water resources models. The tool is flexible and generalized in the system configuration and data input, in the attribution of planning and operating policies and in processing output.

As illustrated by Manca et al. (2004), in WARGI there are procedures that create graphic objects to handle the input of data and parameters and the creation and modification of system elements. The WARGI-SIM module implements the simulation, while the WARGI-OPT module implements the optimization algorithms. The construction by means of independent modules makes it possible to use the DSS either for system optimization alone or for simulation alone.

Unlike the usual simulation models, which were designed to describe system behavior using complex specific algorithm rules embedded in the code, the WARGI-SIM module (Sechi and Sulis, 2007) defines a set of water allocation rules [r] based on a set of user-defined preferences and priorities [v]. Strategic reservoirs and priority levels for demands are assigned by the user. For each strategic reservoir, the user can also define a reserved volume as a function of the period of the year. When storage volume is within the reserved zone, withdraws for demands are decreased to satisfy entitled demands only. In such cases, based on a hierarchical list of resources and demands, additional flows could be activated to meet non-priority demands from alternative or marginal resources, or temporary restrictions could limit some of these non priority demands. In this 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 in a reactive approach. The reactive approach includes more expensive and stronger impact measures to be taken later, during the drought event, without reducing the system’s vulnerability to future drought events.

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-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 of water scarcity. 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 the analysis of a water system for a time horizon T with a time step t (Figure 1), WARGI-OPT forecasts the system evolution on a time horizon Δ at each synchronization period τ_i based on the current water system state and a future hydrological synthetic 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. The model can be written as follows:

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

subject to

$$A[x_i, x_j] = b_g \quad (2)$$

$$F\left(Y, [x_i, x_j]\right) \geq 0 \quad (3)$$

$$l \leq [x_i, x_j] \leq u \quad (4)$$

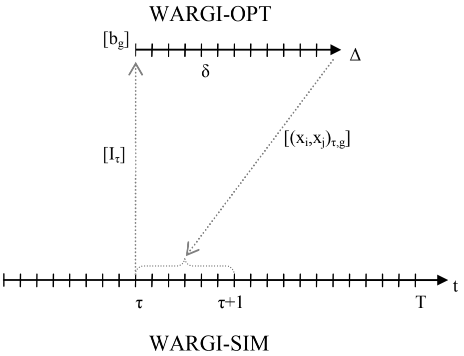

Figure 1. Mixed optimization-simulation approach for drought mitigation measures in WARGI-DSS.

The set of costs [c_γ] is related to the project variables [Y], c_i represents operative, maintenance, and replace costs (OMR) or user-defined costs along transfer arcs, and c_j represents deficit costs based on demand priority ranking. The variables [x_i ,x_j] are the subsets of the flow variables x , respectively related to flows along the multi-period network and to flows along "dummy deficit arcs", (Sechi and Sulis, 2007). The parameters l and u are the lower and upper bounds on [x_i , x_j].

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_τ]:

$$z_\tau = f_1\left(\left[x_i, x_j\right], v\right)_\tau \qquad \tau = \tau_1, \tau_n \qquad (5)$$

In the simulation, water allocation (X_t) in the system is the solution of a minimum cost flow problem between resource and demand nodes in the direct graph representing the water system. These preemptive measures [z_τ] can modify the water allocations (X_t) from those previously defined using the allocation rules [r] and user-defined preferences and priorities [v].

Consequently, during the subsequent periods until τ_{i+1} , we can define:

$$X_t = f_2(z_\tau, v, r) \qquad t = (\tau_i, \tau_{i+1}) \qquad (6)$$

As is well known, the simulation time horizon T should be extended for several decades in order to obtain a correct estimation of system performance. The definition of the optimization time horizon Δ, the hydrological scenario, and the costs of penalties associated with the preemptive measures are key aspects in this approach (Sechi and Sulis, 2007).

In the case of water scarcities more severe than those forecasted by WARGI-OPT, the preemptive measures [z_τ] do not make it possible to overcome the water scarcity, and WARGI-SIM introduces further restriction measures [s_t] in a reactive approach. These reactive actions are defined following the state indicators of the system [I_t], the user-defined preferences and priorities [v], and the pre-defined water allocations [X_t]:

$$s_t = f_3(I_t, X_t, v) \qquad t = (\tau_i, \tau_{i+1}) \qquad (7)$$

In multi-reservoir systems, the state indicators [I_t] to trigger reactive measures are usually the reservoir storages. The time extension and effectiveness of these temporary reactive actions [s_t] may vary with the system resiliency and the effectiveness of the measures [z_τ] already implemented in the proactive approach.

The goal of this mixed optimization-simulation approach is to define the best combination of drought mitigation measures that minimize the economic impact of drought in the water supply system. The economic response function R is the sum of the costs associated with the construction of new works in the system ([C_γ]), OMR costs ([C_{OMR}]), and costs related to mitigation measures ([C_{PD}] and [C_{NPD}]):

$$R = C_{\gamma} Y + \sum_{\tau_i} C_{PD} z_{\tau} + \sum_{t=1}^{T} C_{NPD} s_t + \sum_{t=1}^{T} \min\left(C_{OMR} X_t\right) \qquad (8)$$

[C_{PD}] and [C_{NPD}] are associated with the drought mitigation measures in the proactive and reactive approaches, respectively. [C_{PD}] and [C_{NPD}] include the OMR costs for drought measures, agency income lost from reduced water sales, and reduced consumer surplus due to these measures.

4. THE AGRI-SINNI WATER SYSTEM

The Agri-Sinni water system (Figure 2) is located in the Basilicata region (Southern Italy), and supplies water to the Puglia and Calabria regions as well. The main reservoirs in the system are Monte Cotugno (capacity of 556·10^6 m^3) and Persusillo (capacity of 159·10^6 m^3) along the Sinni and the Agri Rivers, respectively. Marsico Nuovo and Cogliandrino are single purpose reservoirs (respectively for irrigation and hydroelectric use) with small regulation capacities. Four intake structures (Agri, Sarmento, Sauro, and Gannano) were constructed on the main rivers for diversion of water.

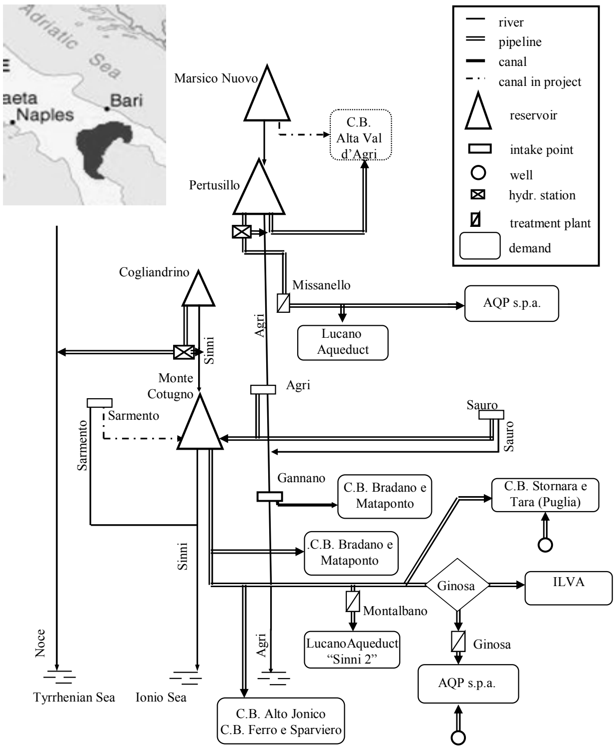

Figure 2. Mixed optimization-simulation approach for drought mitigation measures in WARGI-DSS.

Table **1**. Statistical indexes of inflows (1983-2005).

Stations	Mean (m^3·10^6/ year)	Stand. Dev. (m^3·10^6/ year)	Max (m^3·10^6/ year)	Min (m^3·10^6/ 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

Based on the observed monthly inflows at Monte Cotugno and Pertusillo over the period 1983-2005, the inflows in other sections of interest in the basin were generated using a multiple linear regression method. The inflow series accurately represent the severe water scarcities in the Agri-Sinni that occurred in the years 1989-1990 and 2001-2002. Table 1 shows the main properties of the hydrologic series.

Urban, industrial (ILVA in Figure 2), and irrigation demands (C.B. in Figure 2) are 295.8·10^6 m^3/yr, 12.6·10^6 m^3/yr, and 240·10^6 m^3/yr, respectively. The mitigation measures were chosen to preserve the priority demands for urban and industrial water requirements. Consequently, only the evaluation of system performance for irrigation uses is reported when the proactive and reactive measures are implemented to face drought events.

Before applying the mixed simulation-optimization approach, a simulation-alone analysis using the WARGI-SIM module was carried out. The system simulation considered the time horizon T covering the years 1983-2005, and the unit time period t was equal to 1 month. The results provide an assessment of the system's ability to address water shortage situations when only reactive measures are implemented in the Agri-Sinni system. Moreover, these simulation results help us assess the benefits of the preemptive measures defined by the mixed optimization-simulation approach.

To identify the state indicator values of the system [I_t] as triggers of the reactive measures, reserved storage volumes were defined in Monte Cotugno and Pertusillo, in order to assure the full satisfaction of urban and industrial demands. The reserved volumes were defined as monthly functions of cumulative future higher priority demands:

$$V_{res,t} = \sum_{j=t}^{Oct} k\left(R_{urb} + R_{ind}\right)_j \qquad j = \{Mar, Apr, May, Jun, Jul, Aug, Sep\} \tag{9}$$

The coefficient k must be carefully defined to avoid unnecessary restrictions. The allocation policy requires the frequent implementation of reactive measures. Mainly, reactive measures in the Agri-Sinni system consist of reductions in irrigation water availability by mandatory percentage restrictions of supply and temporary restrictions limiting the irrigation of some annual crops. Thresholds of implementation of the measures were statically identified as follows:

1. When the deficit is between 0% and 50%, a temporary restriction is introduced and irrigation for perennial crops is assured to avoid damage to the trees;
2. When the deficit exceeds 50%, ration allocations as a percentage of use during normal periods are created.

Results obtained by WARGI-SIM alone (Figure 3) had highlighted the lack of effective measures in a planning strategy to increase the system's reliability in the case of intensive drought. A maximum annual reduction of 80.3%, and 5 years where reductions exceed 50%, would determine unsustainable stress conditions in the irrigation sector.

Advance warning of drought can trigger a number of drought management alternatives, as shown in Table 2. Additional long-term measures may also been considered by the authorities (e.g., construction of desalination plants or over-exploitation of aquifers), but they are not included in this study because of their uncertain fates.

Table **2**. Drought mitigation measures in the Agri-Sinni system.

Type of Measures	Pro-active approach (z_τ)	Reactive approach (s_t)
Supply Increase	Reallocation available resources Use of additional sources	
Demand Reduction	Pricing Use of agronomic techniques	Temporary restriction Percentage rationing

In the mixed simulation-optimization approach, proactive measures have been identified by WARGI-SIM using flows along the supply and deficits arcs in the system graph. In WARGI-OPT, the forecast was done using the beginning of April as the synchronization time (τ_i = 1st of April), one year ahead as the time horizon (Δ = 1 year), and a month as the time step (t = 1 month). There is an obvious trade-off between the assumed criticality of the hydrological series in WARGI-OPT and the effectiveness of the drought mitigation measures in WARGI-SIM. Highly pessimistic assumptions suggest unnecessary preemptive measures, whereas over-optimistic assumptions provide no adequate actions in setting up the preemptive measures. According to the results of the sensitivity analysis, the 3rd worst annual observed series of monthly inflows was used by WARGI-OPT. The preemptive measures [z_τ] are dynamically defined by WARGI-SIM based on [x_i ,x_j] obtained by WARGI-OPT and the user's preferences and priorities.

As shown in Figure 3, preemptive measures are implemented in advance of the start of drought based on information provided by WARGI-OPT. In the mixed optimization-simulation approach, the preemptive measures do not require the adoption of any rationing and significantly reduce the implementation of temporary restrictions (Figure 3). At the cost of distributing reductions over a larger period, the mixed optimization-simulation approach also reduces the total amount of shortages due to the proactive and reactive actions. The total shortages in the irrigation demand are 67.8% instead of 80.3% (WARGI-SIM alone) during one of the most serious

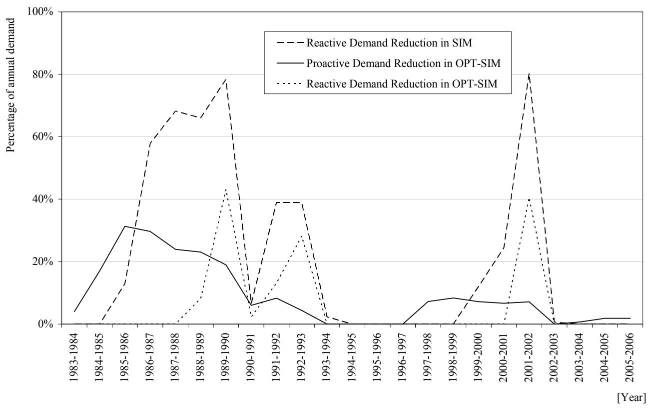

Figure 3. Mixed optimization-simulation approach for drought mitigation measures in WARGI-DSS.

scarcity periods (2001-2002). In addition, a significant reduction of the reserved volume for urban and industrial demands is presented with the coefficient k in (9), decreasing from 1.0 to 0.7.

5. DISCUSSION AND CONCLUSIONS

Drought mitigation plans should include drought indicators, triggers and measures to be adopted in advance. Support and information may come from DSSs that estimate impacts of alternative and management decisions. They are used to help authorities to reach an improved understanding on how the water resource system may work in the future. The implementation of drought plans should include an extend public and DSS must be understandable also for non-expert users. Using DSSs, also stakeholders could reach a common vision of how the system works. In our view, that could be added to close the gap between theory and practice in the application of DSSs facing drought conditions. The major advantage of the proposed mixed simulation-optimization approach is the ability to dynamically consider measures based on different future scenarios of the system evolution.

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