

MITIGATION OF DROUGHT EFFECTS ON WATER SUPPLY SYSTEMS

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ABSTRACT

When a drought occurs, institutions and stakeholders react with impact assessment, response, recovery, and reconstruction activities to return the region to a pre-disaster state. These responses to the hazard effects often produce inefficient technical and economic solutions. The proactive approach to drought management is a more effective mitigation strategy. Risk assessment procedures and optimization of mitigation rules are particularly required for the more vulnerable parts of the systems: the water supply systems. For their management, water storage, as well as demand fluctuation, play an important role. For that reason a dynamic indicator relating supply and demand is required in order to identify situations when there is risk of water shortages. The hydrologic state of the system is evaluated defining some threshold values, expressed in probabilistic terms. Threshold values can be linked to specific actions in an operational context in different levels of severity, like the normal, pre-alert, alert and emergency scenarios.

A simplified model of the water resources system is built to evaluate the threshold values and the management rules. The threshold values are defined considering the probability to satisfy a given fraction of the demand in a certain time horizon, and are validated with a long term simulation that takes into account the characteristics of the evaluated system. The levels and volumes in the different reservoirs are simulated using 30-40 years time series. A demand reduction is related to each threshold level. The rules to manage the system in drought conditions, the threshold levels and the reductions are optimized using long term simulations with different hypothesized states of the system. The critical situations are assessed month by month in order to avoid conditions of total water shortage. Synthetic sequences of flows with the same statistical properties of the historical ones are produced to evaluate the performances of the system. The idea is to test it under a variety of conditions using longer sequences of flows than historically available containing more extreme events than observed.

The methodology is applied to the urban area Firenze-Prato-Pistoia in central Tuscany, in central Italy.

1 INTRODUCTION

Institutions, organizations and individuals usually react to a natural hazard and to the resultant disaster with impact estimation, reaction, recovery, and reconstruction activities in order to drive the area back to a pre-disaster state (Godschalk, 2003).

Public opinion considers drought to be a rare and random event. As a result a reacting approach is used for each event. This approach often results in inefficient technical and economic solutions since actions are taken with little time for evaluating optimal actions and stakeholder participation is very limited. In addition, in most drought-prone regions, another drought event is likely to occur before the region fully recovers from the previous event. Since drought is a normal part of climate, strategies for reducing its impacts and responding to emergencies should be well defined in advance.

The risk management or proactive approach to drought management is a more effective mitigation tool than the crisis management or reactive approach (Wilhite et al., 2000). It includes all the measures designed in advance, with appropriate planning tools and stakeholder participation. The proactive approach provides both short term and long term measures and includes monitoring systems for a timely warning of drought conditions (Wilhite, 2008).

Droughts always start as a meteorological phenomenon with persistent precipitation deficiencies over a region. After a while, these deficiencies deplete soil moisture content and produce impacts on natural and rainfed agricultural systems, which have only a limited capacity to store water in the soil. Prolonged absence of precipitation, soil moisture deficit and decreasing in river flows do not necessarily mean scarcity in an artificial water resources system, because water can also be supplied from natural or artificial reservoirs: snow pack, aquifers, and regulation dams can sustain water demands during periods of meteorological drought. If drought conditions persist, reservoirs in the system are depleted of their reserves, and a period of water scarcity could start (Rossi, 2000). Moreover shortages risk depends even on demand fluctuation and on the actions carried out in order to reduce drought effects. For those reasons, dynamic indicators, relating resources and demand, are required in order to identify the probability of occurrence of situations with a certain risk of water shortages (Garrote et al., 2008).

Volume into the reservoirs supplying the system is chose in this work as operational indicator to evaluate the probability of failures in water supply systems (Figure 1). In particular, operating rules for drought mitigation are developed defining some threshold values, expressed in probabilistic terms. An optimization process is used to delineate the rules that best works on the system. A simplified model of the water resources system is settled up. The threshold values are validated with Monte Carlo simulations and the operating rules with long term simulations, both performed with the software WEAP - Water Evaluation And Planning system. The critical situations are assessed month by month in order to evaluate optimal management rules during the year and avoid conditions of total water shortage. The methodology is applied to the urban area of Firenze in central Tuscany, in central Italy.

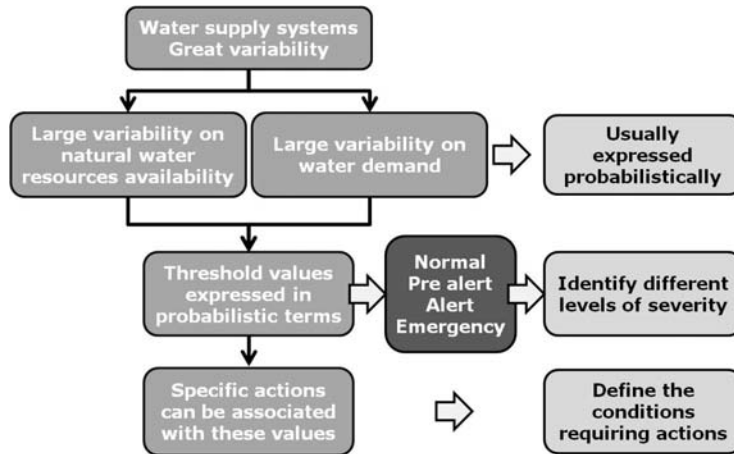


Figure 1. Drought risk assessment: methodological approach flow chart.

2 USE OF A DECISION SUPPORT SYSTEM (DSS)

Under water scarcity conditions, simulation models provide an efficient way to predict source-demand interactions and the impacts of rule modifications over time and space, in order to set the most appropriate drought mitigation measures.

The complexity of the systems suggests evaluating the area with decision support systems (DSS). In fact, the concept of DSS has emerged to help decision-makers to answer specific questions by facilitating the use of models and databases in an interactive way (Andreu et al., 1996), to explore alternative courses or actions and to predict their impacts (Rossi, 2003). Since in Mediterranean drought prone areas the systems are supplied by surface water resources stored in reservoirs (Rossi, 2003), the project focused on the management of water supply reservoirs under drought conditions.

The WEAP (Water Evaluation and Planning System) software, developed by the Stockholm Environment Institute's U.S. (SEI, 2005), is implemented for the analysis. It is a reservoirs, rivers and user system water balance accounting model that allocates water from surface and groundwater sources to different types of demands.

Several software tools have been evaluated and in the end it was decided to use WEAP mainly for three reasons. First of all because it can simulate a broad range of natural and engineered components of a basin or sub-basin system. Secondly because it is user friendly and it permits to simulate and to compare different possible scenarios, and finally because it has been used in several applications and there is a general agreement about its performances among the scientific and non-scientific communities worldwide.

3 MODEL IMPLEMENTATION OF THE STUDIED AREA

The methodology is applied to the urban area of Firenze in central Tuscany, in central Italy. The investigated area has a surface of 1.230 km². It covers the Sieve River

basin, a right affluent of Arno River, and the Arno River basin between the confluence with Sieve River and the city of Firenze.

It includes Bilancino reservoir, located in the upper part of Sieve catchment. The dam is an earth fill dam with a silt core with a conservation storage capacity of 62.50 Mm³. The reservoir catchment has an area of 149 km², generating mean annual inflows of 78.37 Mm³, with higher values in spring and autumn. Therefore annual inflows frequently exceed the storage capacity of the reservoir. Most of its releases are used to satisfy ecological flow requirements and to supply several municipalities in the area of Florence.

A simplified model of the area, represented in Figure 2, with the 2005 setting and the 1970-2005 historical inflows is evaluated. Particularly, the response of the system actualized to 2005 with the impulse of the hydrological data of 1970-2005 is evaluated.

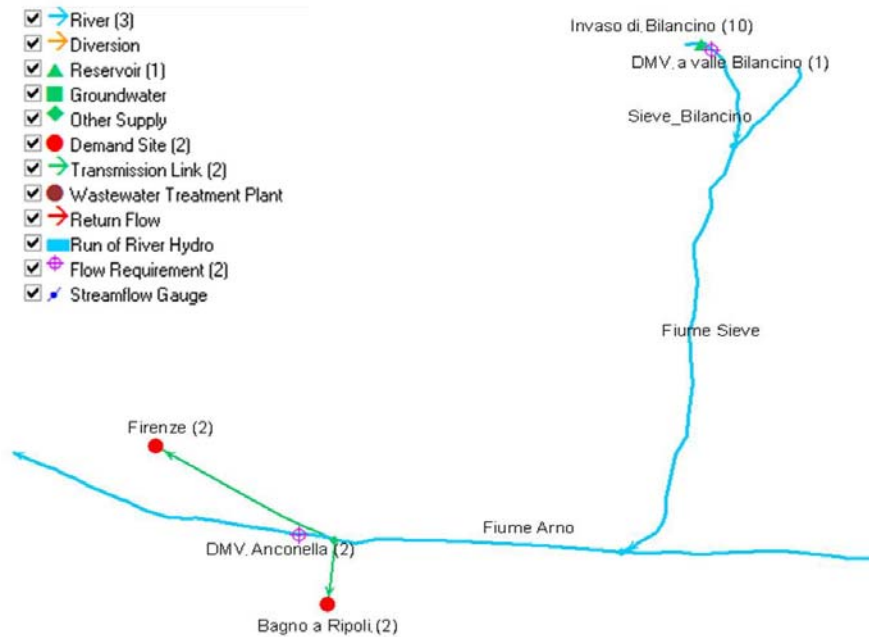


Figure 2. The evaluated model from the WEAP software “schematic” view. Near every site is shown the assigned priority.

The scheme of the system is simplified (Figure 2), considering the reservoir of Bilancino, the two urban demand sites of Firenze and Bagno a Ripoli, three “river systems”: Arno, Sieve and Sieve Bilancino, and two minimum stream flow requirements: the first one on Sieve Bilancino, downstream Bilancino Reservoir, and the second one on Arno, downstream Anconella outlet. WEAP allocates water to meet instream and consumptive requirements, subject to demand priorities, supply preferences or other constraints. In the model the higher priority is given to the flow requirements, then to the municipality demand centres; the lower priority is given to the reservoir filling. Inflows into Bilancino reservoir and Arno and Sieve rivers discharges are evaluated with the historical data of gauge stations by Servizio Idrologico Regionale

Toscana (Regional Hydrologic Service of Tuscany).

The considered demand centres are Firenze and Bagno a Ripoli, which have, according to the census ISTAT 2001, a total of 395'000 inhabitants. The demand patterns are shown in Figure 3.

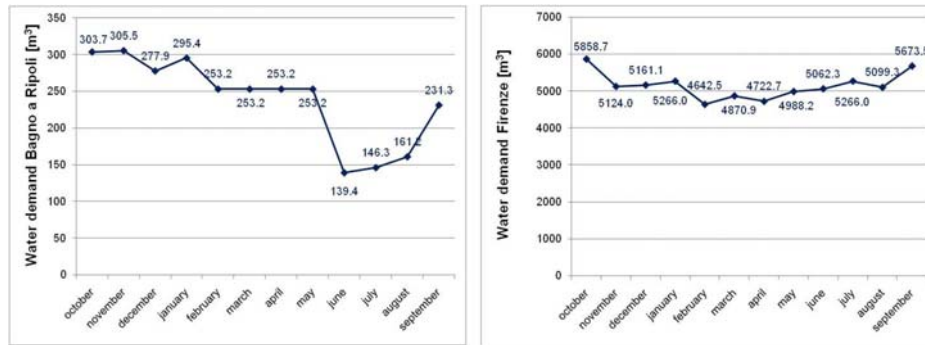


Figure 3. Firenze and Bagno a Ripoli municipalities monthly total demand.

The relationship between water crisis and failure of water supply systems and reservoirs volumes, represented by volume in reservoir – deficit/risk curves, is evaluated performing short time simulations. Every simulation is performed considering a time lag of one year.

Simulations were performed using an ensemble of 420 inflows, consisting each in 12 consecutive monthly recorded inflows. The set is obtained by taking each time a different first month within the considered time series of 35 years, from January 1970 to December 2005. As boundary conditions is used the water stored into the reservoirs: 25 different levels in the reservoir at the beginning of the simulation were considered.

4 MITIGATION OF DROUGHT EFFECTS

The operational implementation of drought mitigation measures requires a connection between the system of drought indicators and selected rules. A set of measures associated to a drought scenario are activated when a given drought indicator reaches a predefined level. The correct definition of critical thresholds implies to reach a balance between the frequency of declaration of drought scenarios and the effectiveness of the application of measures. If drought scenarios are declared too early, users are frequently exposed to unnecessary restrictions. If the declaration of drought scenarios is delayed, it may be too late for the measures to be effective.

In this work thresholds are expressed in probabilistic terms that measure the hydrologic state of the system. They define four scenarios associated with different levels of drought severity that are, following the subdivision of Iglesias et al. (2007): normal, pre-alert, alert and emergency scenarios. Definition of the operation rules implies to select the threshold values and to define the required demand reduction at every stage.

The threshold values and the rules to be imposed on the system for the drought mitigation are optimized through simulations of the water supply system under drought management rules for two long term conditions. The system is evaluated with the

infrastructures and the demands of 2005 and with the inflows and precipitation of the period 1975-2005. To adapt to current requirements imposed by the Water Framework Directive the ecological streamflow requirements have been assigned a higher priority of allocation than the demand centres.

The objective of the optimization is to minimize the deviation of each supply from the respective demand targets while the system is operating under drought management rules. The objective function ZF is defined as an aggregate of the squared ratio between d , deficit on water supply, and Su , designed water supply, for all the demands i and all the time steps t :

$$ZF = \sum_{t=1}^T \sum_{i=1}^N \left(\frac{d_{ti}}{Su_{ti}} \times 100 \right)^2 \quad (1)$$

with $i=1, 2; t=1, 2 \dots T$.

To let the optimization procedure seek the solution which reduces the risk of extreme supply shortages, this function penalizes a large deficit more than a number of smaller deficits amounting to the same volume.

The process uses a trial and error procedure based on the dynamic programming approach that converts an n -stage decision problem into a series of n single-stage decision problems.

5 DISCUSSION OF RESULTS

Once the simulations were performed, the results were processed to obtain, for every month, the required storage volume in month m , vm dr , for a given deficit level di and risk level rj . Some graphs are built to represent the results. In every graph a first variable is fixed and the variance of a second one, function of the third and the fourth, is represented.

In the first group of graphs (Figure 4) the stored volume in four reference months, function of the deficit, function of risk, is represented. The chosen months are October, January, April and July, the first ones of each hydrologic season. The deficit is represented with four curves, function of four level of risk: 5%, 15%, 30% and 50%. These levels are chosen because are quite representative. There is no deficit till the critical volume is reached, and then there is a nearly linear correlation between stored volume and deficit.

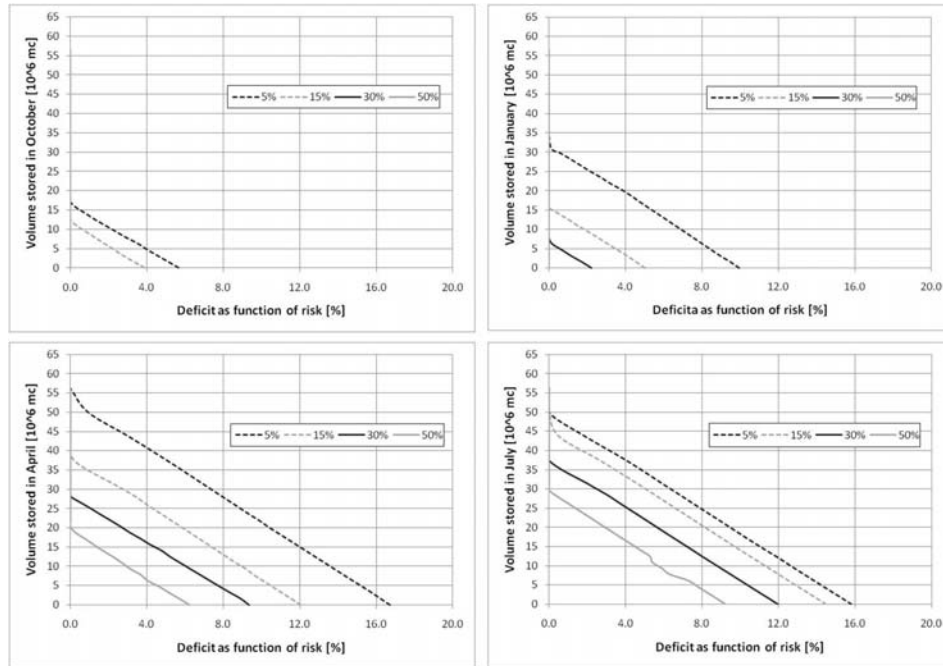


Figure 4. Results of: stored volume in four reference months (October, January, April and July) function of deficit for four selected risks (5%, 15%, 30%, and 50%).

In the second group of graph (Figure 5) the required volume month by month is represented. Four deficit levels were considered: 0%, 2%, 5% and 10% of the demand. These levels are relevant for decision making, because they correspond to significant degrees of socioeconomic impacts. For each deficit value, the required storage volume at the beginning of every month was computed for different risk values. A total of six risk values were considered: 0%, 5%, 10%, 20%, 30% and 50%.

Required volumes are maxima in summer and minima in winter, in accordance with hydrologic regime. For the 10% deficit the required volume is very low: the system is not totally depending from the reservoir.

The curves presented in Figure 5 are used for the mitigation procedure. System performance under several combinations of threshold values V and several values of demand restriction r for each drought condition are evaluated through long term simulations. An iterative optimization process is carried out: for each stage a set of candidate threshold values, taken from the previous groups is considered. For each candidate value a demand restrictions in $(r_{\min}-r_{\max})$ is considered. Simulations through WEAP software are repeated for different values and restrictions.

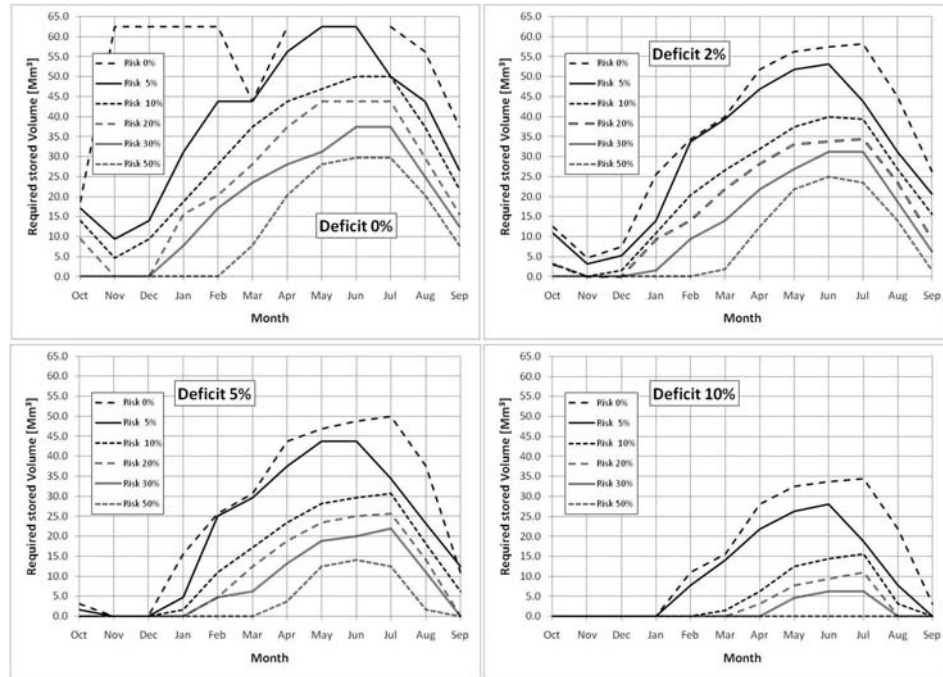


Figure 5. Required reservoir volumes in different months for four considered deficits (0%, 2%, 5%, 10%) and six degree of risk of failure (0%, 5%, 10%, 20%, 30%, and 50%).

The threshold levels that perform best are shown in figure 6. The pre-alert thresholds require that in late spring and at the beginning of summer the reservoir should be quite full in order to minimize the effects of the arid summer months, while in November and December the reservoir can be quite empty. The alert and emergency thresholds require a volume starting respectively on December and January and the maximum volumes respectively on May and July. In Table 1 the demand restrictions related to each threshold levels are reported.

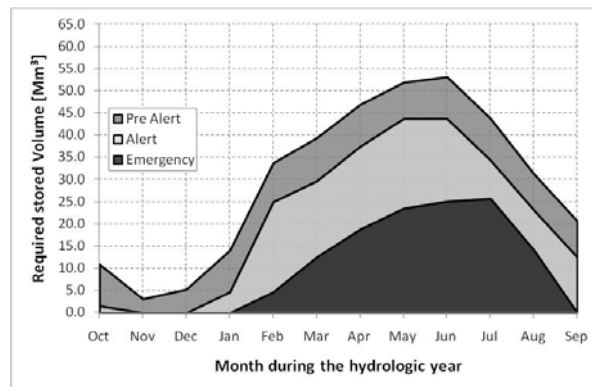


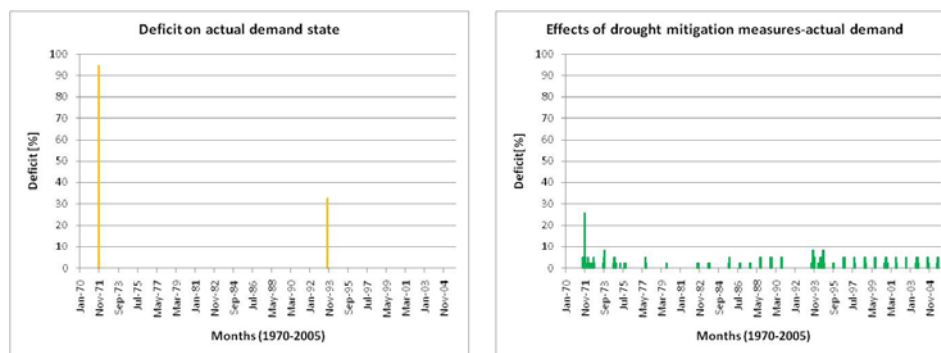
Figure 6. Monthly reservoir volumes as threshold levels for the different drought management scenarios.

Table 1. Management parameters: threshold levels and related imposed demand reduction.

State of the system	Threshold levels	Demand reduction (%)
pre alert	risk 5% - deficit 2%	2.43
alert	risk 5% - deficit 5%	5.18
emergency	risk 20% - deficit 5%	8.40

The effects of the threshold levels and demand reductions applied to the normal state are shown in Figure 7.

There is a deficit in the event on 1971, but its effects are reduced of about 70%. The procedure is not able to avoid completely the effect of this drought because of the celerity with which the system enters in the alert and emergency scenarios. The system enters more than 20 times in the pre alert scenario and 4 times in the emergency one. With these simulations a pre-alert state evolves into an alert or emergency state about the 72% of times. The 77% of times the system recovers from an alert state without reaching the emergency level. Therefore only the 22% of times that the system enters in the pre-alert state it reaches an emergency state. The system enters in the pre-alert state on August and September about the 60% of the times and in the alert state about the 20% of times.

**Figure 7.** Effects of drought mitigation measures, time span 1970-2005: comparison of deficits between the situation without rules (left) and with rules (right).

Synthetic sequences of flows are produced to evaluate the performance of the system. The idea is to test it under a variety of conditions, and with longer sequences of flows than historically available. The implication is that long sequences will contain more extreme events than observed and thus be a more stringent test of the system. It is required that the synthetic flows should have statistical properties which are indistinguishable from the historical flow. A Markov or first-order auto-regressive (ARMA) model, applied to stationary and standardized annual or monthly series (Lawrance and Kottegoda, 1977) is used to generate synthetic flows. The different sites are considered correlated. Once that Arno streamflows are calculated, Sieve and Sieve Bilancino discharges are generated using a correlation coefficient. A 200 years sequence of flows is produced.

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as a function of the volume stored in the reservoir. Some probability curves are built to show the results. Results are shown by some probability curves: required volumes are maximum in summer and minimum in winter, in accordance with hydrologic regime.

A procedure for the mitigation of drought risk is also proposed, based on the results of the risk assessment. Some proactive measures, affecting the demand, are suggested. Four scenarios (normal, pre-alert, alert and emergency) associated with different levels of severity of drought are defined and mitigation rules able to reduce the effects of most severe droughts are connected to each scenario. This procedure can be applied to all the water supply systems depending on reservoirs, once that their peculiarities are taken into account.

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