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Operational drought management via risk-based conjunctive use of water

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Effective mitigation of drought impacts in water supply system management strongly depends on clearly defined indicators describing the level of risk of shortages due to drought that the system has to face in a short term horizon. Such a shortage risk plays a central role in the reduction of drought impacts and can be evaluated with the objective to trigger predefined mitigation measures included in a Drought Management Plan to be prepared in advance.

The paper presents a methodology for a risk-based short-term drought management of a water supply system considering three management policies of the water supply system with reference to drought (normal, alert and alarm). The methodology presents an indicator of risk of shortages due to drought based on Montecarlo simulation enabling water managers to take decisions considering the probability of shortages in the next future as a function of the decisions taken in the present also considering additional groundwater resources. Application to a water supply system in Sicily including a reservoir supplying competing uses indicates the potential of the methodology to reduce drought impacts, to support decision processes and to implement an effective conjunctive use of water.

Keywords: *Drought risk management, Montecarlo simulation, Conjunctive use of water*

1. INTRODUCTION

Drought can be defined as a temporary (random) condition of “severe” reduction of water availability compared to “normal” values extending along a “significant period of time” over a “large region” (Rossi, 2000). The effects of drought on water supply systems in terms of water shortages greatly depends on the characteristics of water storage facilities, their operating rules, the temporal distribution of water demands as well as on the actions to reduce drought impacts. The main decisional problem of the operation of a water supply system under drought conditions is when and how to activate adequate mitigation measures (i.e. rationing policies and/or use of additional water resources) in order to avoid future severe shortages. Due to the uncertainty of future water shortages, the decision should be taken on the basis of an assessment of shortage risk due to drought. Thus, the choice of one or more risk indicators able to support the decision process in the management of water supply systems located in drought-prone areas becomes crucial to trigger mitigation measures against drought impacts. In any case, it is largely recognized that mitigation measures have to be defined within appropriate drought plans (WS&DEN, 2007), also in order to reduce the probability of shortage and maximize potential conjunctive use of available water.

Different definitions of drought risk have been proposed in literature (Cancelliere et al., 2009). Some definitions, widely used for natural disaster mitigation like earthquakes or floods, are based on the expected damages, namely the combination of the probability of an adverse event (hazard) and of the value of the elements at risk. However, when dealing with water supply system management under drought conditions, it may be more convenient to adopt water shortage risk indicators, that, taking into account the probability of deficits in streamflows, the current reserves in storage facilities and the different management alternatives can measure the risk reduction corresponding to the activation of different sets of mitigation measures (Andreu et al., 2007). These pre-defined measures have to be established according to the different conditions of the water system vulnerability (e.g. normal, alert, alarm) (Iglesias et al., 2007). Within this context, a definition of risk based on the probability of severe shortages in the future may be helpful.

Management of water supply system under drought conditions has been subject of many papers mainly devoted to the definition of operating policy or storage allocation rules. Shih and Revelle (1994) derived demand-management policy rules during droughts or impending droughts for a water supply system with a single reservoir water supply system. The signal used for calling rationing is a trigger volume given in terms of months of demand (as a volume) that are needed in storage. When the sum of actual storage plus anticipated inflow is less than the trigger volume rationing is initiated. Shih and Revelle (1995) presented a mixed integer programming model that operate a water supply reservoir through discrete rationing phases. The model determines the triggers to activate several phases of rationing under the objective of maximizing months without rationing given a limit on the number of months with a second phase rationing. The model provides guidance to the water manager by selection of the signal that should be used in determining the phase of rationing to be activated. Lund (2006) developed storage allocation rules among reservoirs making part of a system operated under drought conditions in order to reduce evaporative and seepage losses demonstrating that balancing storage among reservoirs, a common practice where each reservoir is filled to a similar percentage of its overall capacity, does not minimize water losses during droughts.

Some studies have been carried out with the main focus on integrating early warning system information within drought management of water supply systems. Huang and Yuan (2004) developed a color-coded early warning system for drought management on the real-time multi-reservoir operation. Making use of a new drought alert index characterizing the alert level of drought severity showed that decision support-like systems can help water authorities to make proper decisions in response to potential drought severity. Huang and Chou (2008) introduced a risk-based decision process integrated into a drought early warning system (DEWS) for reservoir operation. Aspects of posterior risk, chances of option occurrences and the corresponding options to given chances, are provided to help decision makers to make better decisions. A new risk index is also defined to characterize decision makers’ attitudes toward risk. Results show that the proposed approach is very practical and could find useful application for reservoir operations. Cañón et al. (2009) used drought frequency index (*DFI*) as a drought indicator for triggering mechanism for multireservoir system operations during drought. The DFI characterizes droughts according to their duration and intensity, using a probabilistic criterion that takes into account the persistence of extreme low precipitation values. Performances with and without the DFI are evaluated, using reliability and resilience indices through a multilevel nonlinear optimization procedure oriented to reduce water deficits on irrigation districts. Results show that the inclusion of the DFI improves the reliability of both reservoirs and water deliveries to users during periods of drought, which reflects an overall improvement of net benefits associated with crop production in irrigation districts. Pulido-Velázquez et al. (2006) presented an integrated hydrologic-economic modeling framework for optimizing conjunctive use of surface and groundwater at the river basin scale. The use of an economic objective function, maximizing the net economic value of water use, provided solutions that optimize economic efficiency in water resources management. Constraints guarantee the feasibility and sustainability of suggested operations. Model results suggested a variety of water management and operation strategies and indicated where significant the economic benefits can be obtained through capacity expansion.

The paper proposes a methodology for managing water supply systems during droughts based on the assessment of risk of future shortages and on the consequent activation of mitigation measures. The methodology is applied to a water supply system in Sicily, considering as mitigation measure, besides rationing of the supply for some uses, conjunctive use of surface and groundwater. The main objective of the methodology is to reduce the probability of severe water shortages on prioritary uses also minimizing the use of expensive groundwater withdrawals. More specifically the methodology is based on the computation of an indicator of shortage probability due to drought through the stochastic generation of streamflow series and Montecarlo simulation of the behavior of the water supply system within a short term horizon starting from its current condition. The risk indicator has been calibrated by considering different short time horizons, several combinations of thresholds of shortage risks evaluated on the supplied water demands and one or more decision months in the year (i.e. months when the decision about the drought state is taken). The implementation of such a risk indicator allows decision makers to manage the water supply system taking into account for probable future drought on a real time basis framework and makes possible a preventive fine-tuned approach to drought by triggering on time mitigation measures such as water rationing on not prioritary water uses.

2. RISK BASED OPERATIONAL DROUGHT MANAGEMENT METHODOLOGY

2.1. Risk indicator of water shortages due to drought

Several drought risk indicators have been defined in literature. Depending on the particular focus, drought indicators have been defined with reference to different hydrological variables with the aim of drought monitoring, early warning, drought forecast evaluated on short or long time horizons. When the interest lies in the operation of a water supply system a possible indicator could be based on estimating the probability of future water shortages as a function of current storage in reservoirs, future streamflows and future demands. Here the proposed drought risk indicator considers the probability of severe shortages over the next *k-months* computed by means of Montecarlo simulation of the water supply system. More specifically, the risk is defined as:

$$R^i_{kM} = P\left[\sum_{j=1}^{k}\left(Def^{\,i}_j > th^i \cdot Dem^i_j\right) > ith^i \sum_{j=1}^{k} Dem^i_j\right]_M \qquad (1)$$

Where R^i_{kM} (for the i^{th} water use) is the probability that the sum over the next *k-months* of the water shortage Def_j in the j^{th} month greater than a fixed percentage of the demand Dem_j exceeds another percentage of the total demand of the i^{th} use, considering as initial condition the actual water stored in the system.

th^i is a threshold (with a different value for each water use *i*) chosen in order to neglect very little monthly shortages considering that the aim of the proposed indicator is to avoid severe shortages in favor of mild water shortages with a more uniform distribution among the explored future *k-months*.

ith^i is a second threshold related to each *i* water use that measures the endurable threshold that can be stood by stakeholders.

Such a risk indicator is computed for each of the *M* different managing options corresponding to normal, alert or alarm conditions of the water system with reference to drought. For instance the different managing options could include water rationing on not-prioritary water uses or the exploitation of groundwater. The main advantages of this indicator of risk of shortage due to drought are that both impacts of probable future droughts over the horizon of the Montecarlo simulation and potential positive effects of conjunctive use of water are directly included in the definition. Furthermore the severity of the water shortages taken into account can be defined according to the specific system under investigation through an appropriate definition of th^i and ith^i thresholds.

2.2. Methodology

The methodology proposed for mitigating the impacts of severe droughts in the management of a water system is based on evaluating, by means of Montecarlo simulation, different values of the shortage risk indicator corresponding to different drought management options of the system and by activating the appropriate state on the basis of a comparison of the different computed risk indicators. The number of possible drought conditions of the system and the consequent actions to be taken corresponding to those states have to be defined by the decision maker. Here, three possible management alternatives of the system with reference to drought (namely normal, alert and alarm) to which correspond different water rationing options of increasing severity as well as different level of exploitation of groundwater have been adopted.

Figure 1 shows the proposed methodology. In particular, the methodology considers the system starting from normal condition and takes into account the water stored in the system at a particular time step (generally at a monthly time scale). For every month in which a decision about the management of the system must be taken, three Montecarlo simulations (one for each considered drought state) are carried out using a large number of synthetic streamflows series. Then, the indicator of risk of water shortages due to drought can be computed obtaining three values of R^i_{kM} for each water use supplied by the system representing the risk of severe water shortages due to drought over the next k-months managing the system through the managing policies defined for each condition.

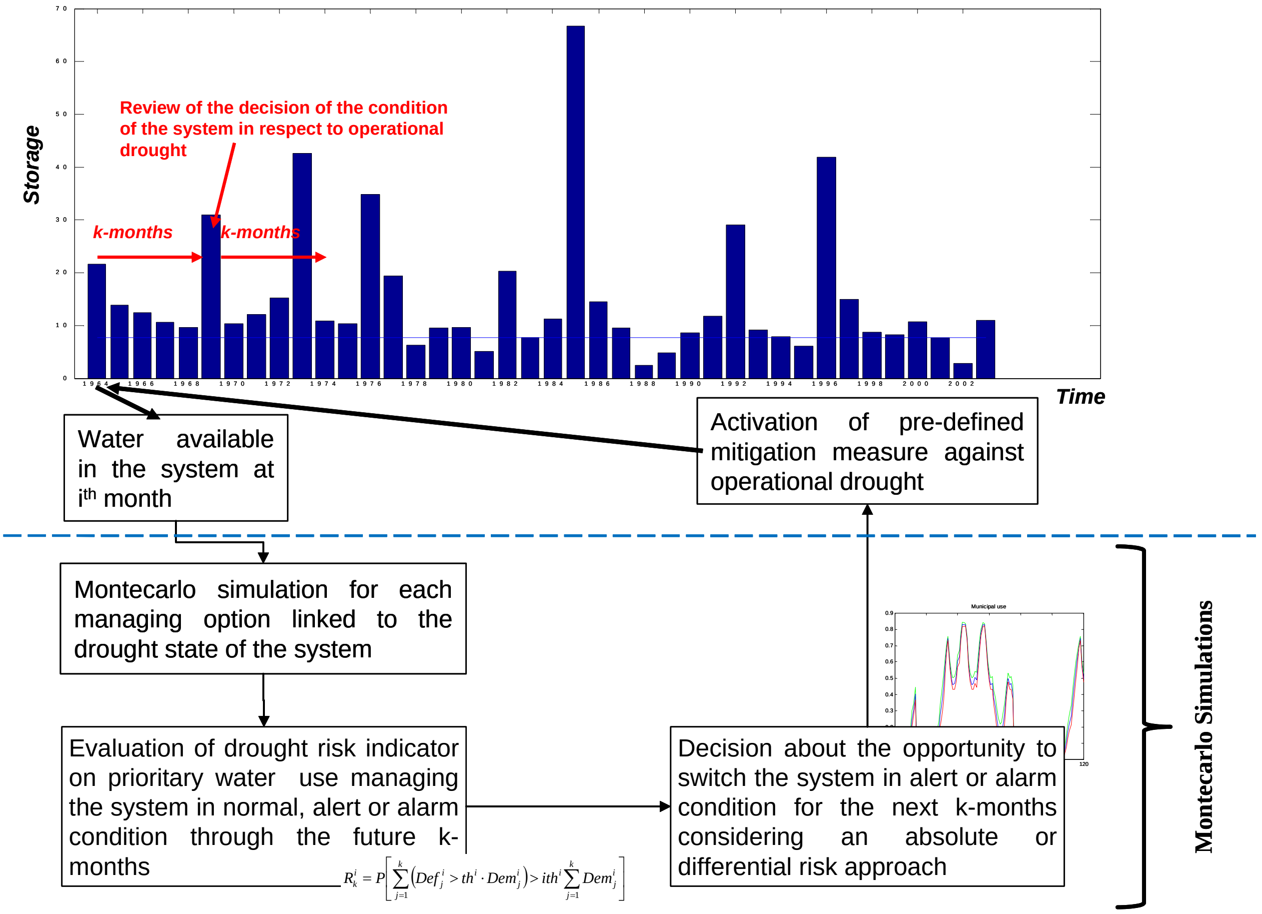


Figure 1 Proposed methodology for the reduction of impacts due to drought within the operation of a water supply system

In order to take the decision about the opportunity to switch the water system management from normal to alert or in alarm and vice versa, a criterion, based on the computed values of R^i_{kM} , has to be set and calibrated for the particular water system under investigation. Here, the adopted decision criterion includes a number of thresholds that have to be calibrated so that the activation of mitigation measures is carried out in a convenient way that reduces the groundwater water exploitation and the probability of severe water shortages due to drought enhancing the conjunctive use of water.

Two different approaches have been explored based on the analysis of the computed values of R^i_{kM} . The first approach consists in switching from one state to another on the basis of the comparison of the indicator value with fixed thresholds. These thresholds express indirectly the willingness of the decision maker to accept the risk of severe water shortages due to drought during the next future k-months.

On the other hand, a second approach (here termed "*differential risk based*") consists in the evaluation of the marginal gain in terms of reduction of risk (*DR*) for switching from normal to alert and from alert to alarm conditions. More specifically, reduction of risk *DR* is computed as:

$$0 \le DR^i_{norm2alert} = \frac{R^i_{norm} - R^i_{alert}}{R^i_{norm}} \le 1$$
$$0 \le DR^i_{alert2alarm} = \frac{R^i_{alert} - R^i_{alarm}}{R^i_{alert}} \le 1 \qquad (2)$$

The above variables *DR* takes into account the potential gain obtainable by the activation of the mitigation measures defined for alert or alarm conditions even if the risk in normal conditions in absolute terms is not very high.

In order to better explain the proposed methodology, an example of its application has been developed with reference to an hypothetical water supply system and water use. In particular, it has been assumed that the decision about switching from one management alternative to another is taken every three months (F-February, M-May, A-Aug and N-November). For each of these four months three values of risk indicator can be computed for managing the system over the k-future months in normal, alert and alarm conditions. Such decision scheduling may be dictated for instance on the basis of fixed meetings with stakeholders representatives, begin-end dates of irrigation season, etc.

In Figure 2 the time series of the indicators of risk of shortages due to drought computed for a particular water use are plotted using a 12 months time horizon and by repeating the computation over a five years time period. As expected $R^i_{alarm} \le R^i_{alert} \le R^i_{norm}$ because the risk indicator decreases due to the activation of the predefined sets of mitigation measures corresponding to the three different conditions of the system with reference to drought.

Considering the first approach two thresholds have been set. In particular, as can be inferred from Figure 2, if the computed risk indicator in normal condition is lower than 0.4 (i.e. less than 40% of probability to get a severe water shortage due to drought over the next 12 months) the system can be managed in normal condition (i.e. without the activation of mitigation measures against drought impacts). If the computed risk indicator in normal condition is within 0.4 and 0.6 the system has to be managed in alert condition and if the computed risk indicator in normal condition is greater than 0.6 (i.e. more than 60% of probability to get a severe water shortage due to drought over the next 12 months) the system has to be switched in alarm condition activating the corresponding mitigation measures against drought impacts.

On the other hand, if the second approach based on *differential risk* is adopted, the decision is taken by comparing the all of the three values of the risk indicator for normal, alert and alarm conditions. Again with reference to Figure 2 two thresholds can be set such as $DR^i_{norm2alert} = 0.3$ and $DR^i_{alert2alarm} = 0.4$ in order to evaluate the opportunity to switch to a more severe set of mitigation measures against drought on the basis of the reduction of risk of shortage. A third low threshold has been defined in order to inhibit the *differential risk approach* for very low value of risk (i.e. $R^i_{k\,norm} \le 0.1$) when maintaining the system in normal condition is almost in any cases the preferable choice.

For example, as depicted in Figure 2, with reference to the month of May of the third year, considering the first approach the indication by the proposed methodology is to switch the system in alarm condition being $R^i_{k\,norm} > 0.6$. On the other hand, considering the differential approach (double arrows), the marginal reduction of risk to switch from normal to alert ($DR^i_{norm2alert}$) is greater than 0.3 suggesting to switch the system in alert but the marginal reduction of risk to switch from alert to alarm ($DR^i_{alert2alarm}$) is less than 0.4 suggesting to avoid to switch the system to alarm conditions because too severe water rationing/groundwater over-exploitation would be imposed without a significant gain in terms of risk reduction.

The first risk approach is simpler than *differential risk* approach and is more easily understandable by decision makers and stakeholders. On the other hand with the *differential risk* approach a larger set of information is taken into account, providing a measure of what could happen in terms of reduction of risk of severe water shortages thus suggesting how and when to trigger defined sets of mitigation measures against drought impacts.

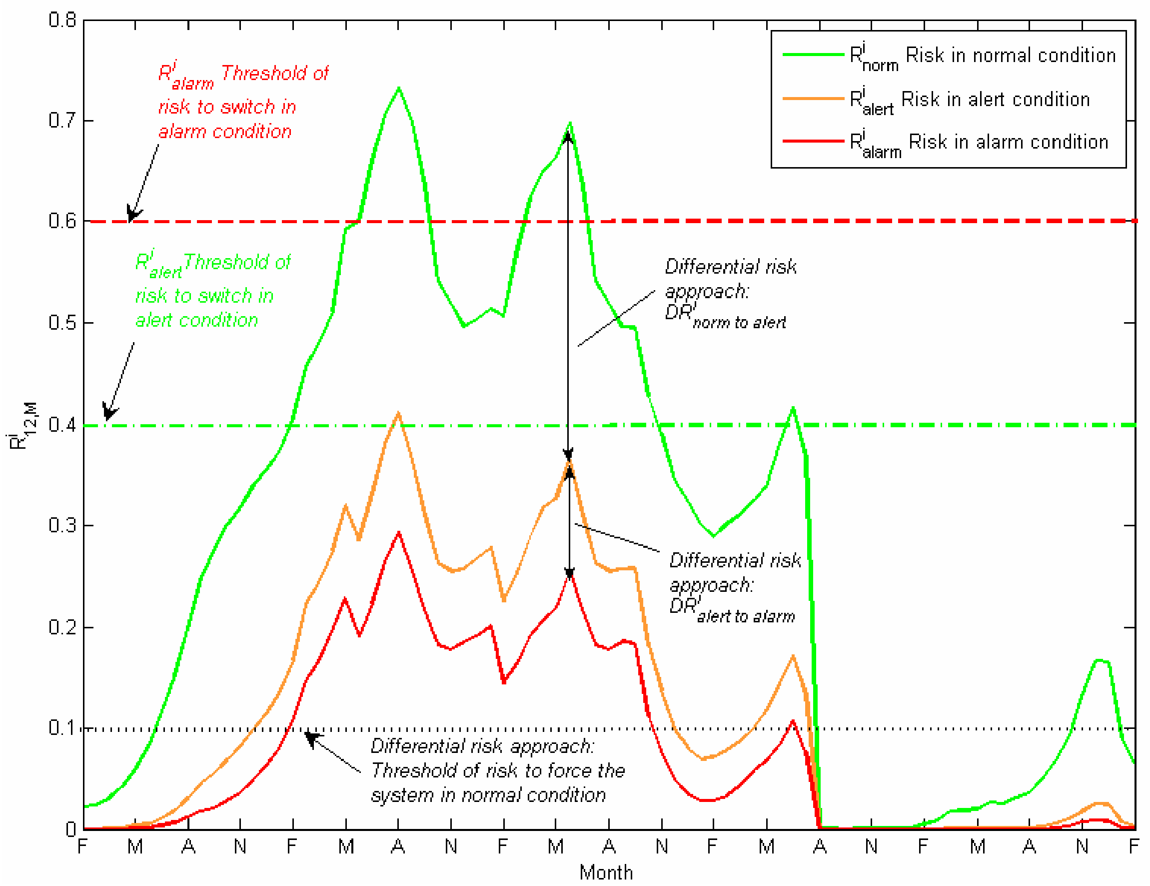


Figure 2 Adopted approaches for the analysis of the computed risk indicators

The computation of the risk indicator, to be repeated every k-months, presents a large number of degrees of freedom that makes it suitable and particularly adoptable for complex water systems including several water sources, different water demands characterized by different priorities, leaving the decision maker the possibility to virtually decide whatever kind of mitigation measure against drought and allowing a continuous revision of the decision taken k-months before.

The methodology needs a number of thresholds to be set for the system under study to be calibrated in advance and included, at a tactical level, within a Water Supply System Management Plan to be developed by Agencies for water supply management. According to the proposed methodology the plan could include both predefined sets of drought mitigation measures and appropriate thresholds so that measures can be timely activated avoiding the worsening of the impacts of drought.

3. CASE STUDY

3.1. Description of the water supply system and water demands

The selected water supply system is located in the Acate river basin, a drought-prone area in the South-Eastern Sicily in Italy. The climatic conditions are typical of a Mediterranean semi-arid region, with a moderately cold and rainy winter and a generally hot and dry summer. The water supply system under study includes the Ragoleto reservoir located on the higher part of the Acate river draining a watershed (about 120 km^2) characterized by heterogeneous soils with a generalized low permeability giving a typical ephimeral behavior to the Acate river with an high variability both in the series of total annual and monthly streamflows (Figure 3 *b* and *c*). The water supply system has suffered several temporary water shortage periods such as in 1978, 1981, 1988-1990, 1994, 2001-2002 mainly due to the occurrence of drought spells and to the uneven distribution of streamflows throughout the year.

Available hydrological data include historical (1964-2003) monthly streamflows of the Acate river at Ragoleto dam section. The complete dataset has been analyzed through a ten years moving average window in order to identify the worst 10-years historical period in terms of reduced flows. Accordingly, the decade starting from November 1985 to October 1995 (Figure 3 *c*) has been used in the following analysis being particularly useful for testing the proposed methodology which principal focus is to reduce impacts of prolonged droughts.

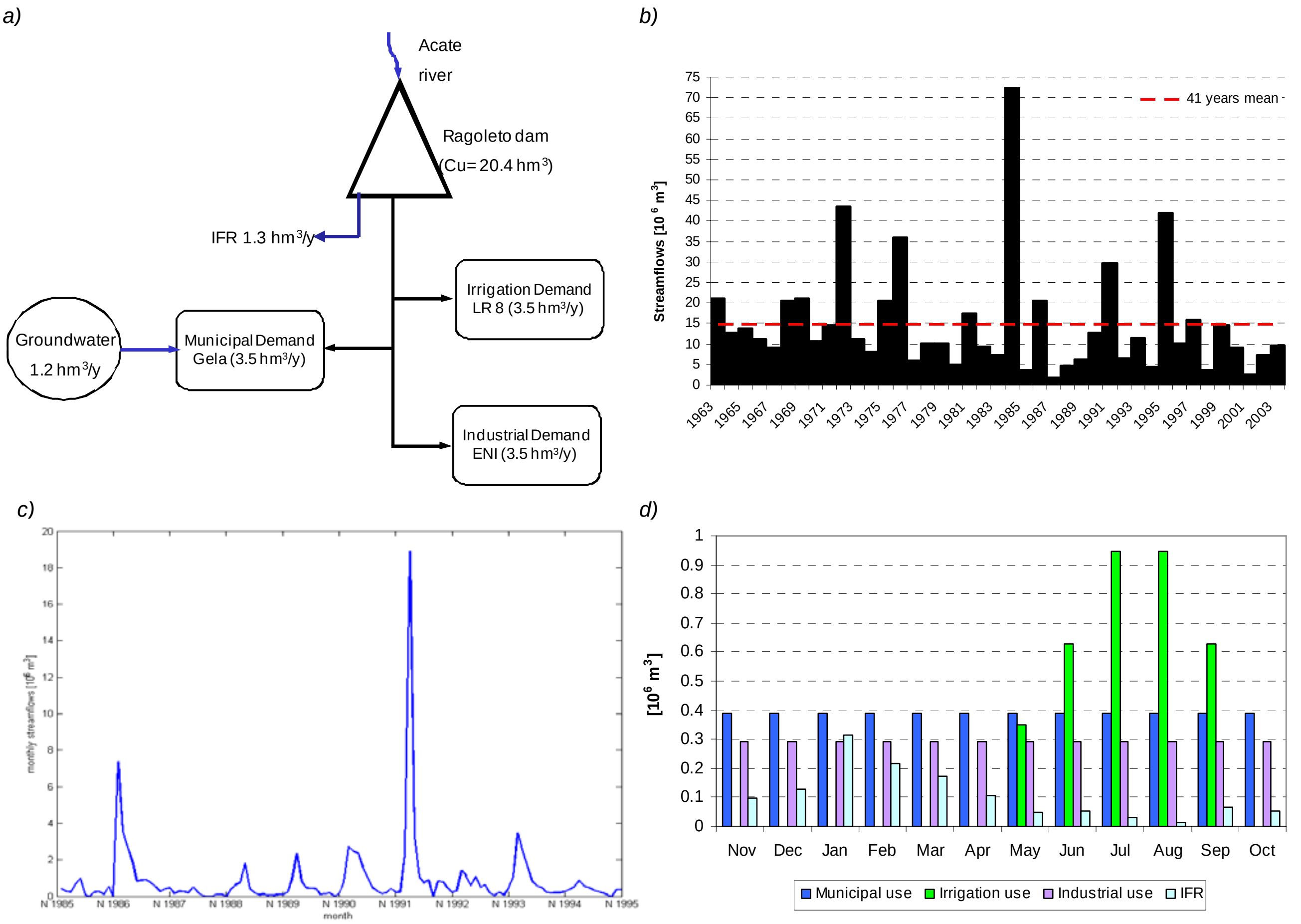


Figure 3 a) Scheme of the water supply system under investigation; b) Complete available annual streamflow series; c) Monthly streamflow series of the selected 10 years drought period; d) Monthly water demands for different uses

Figure 3 *a)* shows the scheme of the water system adopted within the simulation model. Ragoleto reservoir has a maximum storage of about $20.4•10^6$ m^3 and, according to a recent Agreement drafted by the Italian Ministry of Environment, supplies municipal (Gela municipality), irrigation (Land Reclamation Consortium n.8, LRC8) and industrial (National Hydrocarbon Agency, ENI) water uses fulfilling environmental constraints regarding in-stream flow requirements (IFR=$1.3•10^6$ m^3/year) according to the patterns reported in (Figure 3 d).

In particular the agreement indicates a total municipal demands equal to $4.7•10^6$ m^3/year to be fulfilled by Ragoleto reservoir for $3.5•10^6$ m^3/year considering, for the remain amount of municipal water demand, the potential exploitation of groundwater with a maximum of $1.2•10^6$ m^3/year. Unfortunately the agreement does not prescribe any methodology for the allocation of groundwater throughout the year especially during drought periods considering a constant monthly amount of groundwater equal to $0.1•10^6$ m^3/month.

Industrial demand amounts to $3.5•10^6$ m^3/year and it is considered constant throughout the year, whereas the total annual irrigation water demand is still equal to $3.5•10^6$ m^3/year but concentrated in five months with an irrigation season starting on May and ending on September.

3.2. Generation of streamflow series and definition of mitigation measures against drought impacts

The first step for the application of the proposed methodology to the case study is the generation of synthetic streamflow series to perform Montecarlo simulations of the water supply system over a short time horizon in normal alert and alarm condition. The generation has been performed by means of the software SAMS (Sveinsson et al., 2003) considering an ARMA (1,0) model to generate annual values and a disaggregation scheme to generate monthly series. Then, the proposed generation scheme is as follows:

- First, annual data have been transformed, in order to reduce skewness, by means of the relation:

$$X_n = log(Z_n + 0.001) \qquad (4)$$

where Z_n is the original (untransformed) data at year n, X_n is the transformed data approximately normally distributed.

- Then, annual data are generated by means of an autoregressive model (ARMA 1,0):

$$X_n=\phi X_{n-1}+\varepsilon_n \qquad (5)$$

where X_n is the value of annual streamflow at year n, ϕ is the lag-1 autocorrelation of the process, and ε_n is a white noise process;

- Finally, monthly data are generated by means of a disaggregation scheme (Lane,1979):

$$\boldsymbol{Y}_n=\boldsymbol{A}X_n+\boldsymbol{B}\boldsymbol{z}_n+\boldsymbol{C}\boldsymbol{Y}_{n-1} \qquad (6)$$

where $\boldsymbol{Y}_n$ is the vector of the monthly values at year n, $\boldsymbol{Y}_{n-1}$ is a vector of values from the previous year, $\boldsymbol{z}_n$ is a white noise vector and $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ are matrices of parameters.

In Table 1 the comparison between historical and generated annual statistics at Ragoleto reservoir is shown. It can be inferred that the model is able to preserve the main statistics of the observed series and therefore it is suitable for data generation.

Table 1 Comparison of statistics of historical and generated annual streamflow series at Ragoleto

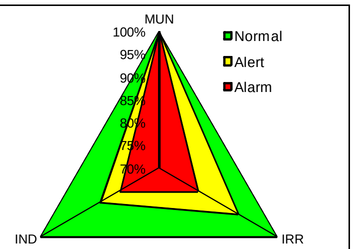
	Mean [hm^3]	St.dev. [hm^3]	CV	Skewness	Min [hm^3]	Max [hm^3]	Autocorrelation coefficient lag 1
Historical	15.02	12.59	0.8381	2.284	2.450	66.66	-0.021
Generated	*14.73*	*11.04*	*0.7152*	*1.699*	*2.877*	*53.15*	*0.076*

In order to assess the validity of the proposed methodology, its application over the selected 10 years period has been tested. In particular, a simulation of the system during the 10 years period has been carried out managing the system according to the proposed methodology, namely taking the decision about the preferable drought management alternative on the basis of the comparison of the shortage risk in the different possible management alternatives. More specifically for every decision month, 5000 series of generated streamflows, each one with a length of 24 months, have been considered in order to take into account possible drought spells that lasts more than a year and by considering the water supply system managed over such a two years future time horizon in normal, alert and alarm conditions.

The three considered management alternatives of the system with reference to drought have been formalized as in Table 2.

Table 2 Mitigation measures against drought impacts adopted in normal, alert and alarm conditions (water rationing and groundwater withdrawal)

	Municipal	*Irrigation*	*Industrial*	Groundwater withdrawal
Normal	100%	100%	100%	No
Alert	100%	90%	85%	Moderate
Alarm	100%	80%	80%	Intensive



The table shows that in normal conditions no rationing is imposed to the different water uses but a conservation policy for groundwater is imposed in order to not exploit aquifers during not drought periods. During alert conditions irrigation and industrial demands are reduced respectively to 90% and 85% of the total monthly amount but a certain percentage of water coming from groundwater is used for municipal use so that, in an indirect way, more water is available for irrigation and industrial uses. Similarly, in alarm conditions restrictions become more severe (80% on irrigation and industrial water uses) but an increased temporary overexploitation of groundwater is allowed. The monthly amount of groundwater to be considered in alert and alarm conditions has been subject of a specific analysis whose results will be showed in the next paragraphs.

3.3. Adopted risk indicator

As showed in paragraph 2.1 the risk indicator of water shortage due to drought needs to be calibrated for the particular water supply system under investigation defining thresholds that measures the endurable threshold that can be stood by stakeholders and which reduction of the monthly demand can be considered tolerable. The general expression of the risk indicator reported in (1) has been calibrated for the case study as in (7).

$$R^{MUN}_{24}\bigg|_{\substack{norm\\alert\\alarm}} = P\left[\sum_{j=1}^{24}\left(Def_j^{MUN} > 0.05\cdot Dem_j^{MUN}\right) > 0.1\sum_{j=1}^{24} Dem_j^{MUN}\right]_{\substack{norm\\alert\\alarm}} \tag{7}$$

From the above expression it can be inferred that, for the Acate water supply system, municipal use has been considered prioritary and decisions on the activation of mitigation measures, though affecting the entire water system management, are taken on the basis of the value of the risk indicator computed for such use over a future time horizon of 24 months that has been considered suitable for including also information on more-than-one-year drought periods. More specifically, the risk indicator represents the probability that over the next 24 months the sum of shortages greater than 5% of the respective monthly demands overcomes the 10% of the sum of demands. The risk indicator has been computed for the three possible conditions of the system with reference to drought that means including on the nested Montecarlo simulations the mitigation measures defined in paragraph 3.1.

Given a particular month, and the corresponding water stored in the reservoir (see Figure 1) once risk indicator has been computed for normal, alert and alarm conditions these values have to be compared with thresholds appropriately defined for the two considered approaches. In the present study the thresholds have been fixed on the basis of a sensitivity analysis, resulting in the values reported in Table 3.

Table 3 Adopted thresholds for the two considered risk approaches

Risk approach 1	
$R^{MUN}_{24\ alert}$	$R^{MUN}_{24\ alarm}$
0.4	0.6

Differential risk approach		
$DR^{MUN}_{24\ normtoalert}$	$DR^{MUN}_{24\ alerttoalarm}$	Low threshold to force the system in normal condition
0.3	0.6	0.1

The proposed methodology has been tested by implementing the two alternative approaches and the mentioned thresholds and mitigation measures through simulation over the selected historical most severe drought decade (nov 1985-oct 1995) and considering that the decision about the activation of the mitigation measures against drought impacts is taken four times during the year (Nov, Feb, Apr, Aug).

A specific analysis has been carried out to define the amount of groundwater withdrawal corresponding to alert and alarm conditions in order to increase the efficiency of conjunctive use of water on the basis of information provided by the adopted risk indicator.

4. RESULTS DISCUSSION

In order to assess the suitability of the proposed methodology to reduce the most severe shortages during droughts, first a simulation of the water supply according to the Agreement draft by the Italian Ministry of Environment (AG. see par. 3.1) has been carried out and the performances of the water supply system have been used as comparison for results obtained by the implementation of the proposed methodology.

Both the first risk approach (R.) and *differential* risk approach (D.R.) have been implemented with specific analysis to the increase of the efficiency of the exploitation of groundwater. In particular Table 4 shows the comparison among performance indices of the water supply system computed for the simulation over the 1985-1995 decade and following the managing policy respectively suggested by AG. or by the proposed R. and D.R. .

With reference to municipal use the implementation of the proposed methodology, both for R. and D.R., leads to a generalized better performance of the water supply system for almost all the indices with reference to the AG, as expected considering that such use is considered prioritary. The increase on performance for municipal water use is substantially obtained subtracting water to the irrigation and industrial water uses as can be inferred by the analysis of the other performance indices that show a generalized worst performance of the water supply system with reference to these water uses. On the other hand analyzing the total amount of water obtained by aquifers the proposed methodology allows respectively a total 42.25% reduction for R. (from 12.00 10^6 m^3 to 6.57 10^6 m^3) and a 17.25% reduction for D.R. (from 12.00 10^6 m^3 to 9.93 10^6 m^3) thanks to the fact that R. and D.R. allow groundwater savings implementing a variable pattern on groundwater withdrawal throughout the year whereas AG. imposes a continuous constant monthly groundwater withdrawal. In particular in Figure 4 is shown the comparison among monthly groundwater withdrawal patterns considering AG., R. and D.R. management.

Table 4 Performance indices of the water supply system under investigation simulated according to the AG. (Agreement draft by the Italian Ministry of Environment), R. (Risk approach) and D.R. (*Differential* risk approach) for drought decade 1985-1995

		Volume based reliability [-]	Probability of monthly shortage [-]	Probability of annual shortage [-]	Mean duration of monthly shortage [month]	Mean duration of annual shortage [year]	Max monthly shortage [10^6 m^3]	Max annual shortage [10^6 m^3]	Sum of squared monthly shortages [10^6 m^3]^2	Total ground water withdrawal [10^6 m^3]
AG.	MUN	0.940	0.108	0.300	4.33	1.50	0.292	1.495	0.702	
	IRR	0.815	0.200	0.300	3.33	1.50	0.945	3.500	5.026	**12.0**
	IND	0.866	0.150	0.400	4.50	2.00	0.292	2.292	1.312	
R.	MUN	0.945	0.108	0.400	3.25	2.00	0.272	1.120	0.568	
	IRR	0.736	0.440	0.500	4.40	1.67	0.945	3.248	6.794	**6.57**
	IND	0.804	0.417	0.700	12.5	1.40	0.292	2.414	1.591	
D.R.	MUN	0.953	0.083	0.200	5.00	2.00	0.272	1.269	0.510	
	IRR	0.768	0.640	0.700	4.57	1.75	0.945	3.140	5.080	**9.93**
	IND	0.806	0.650	0.900	19.5	1.50	0.292	2.098	1.170	

As expected to a groundwater withdrawal reduction obtained for R. and D.R. correspond increased water shortages on irrigation and industrial uses because water is firstly allocated to municipal water use that means less water available for the two other uses.

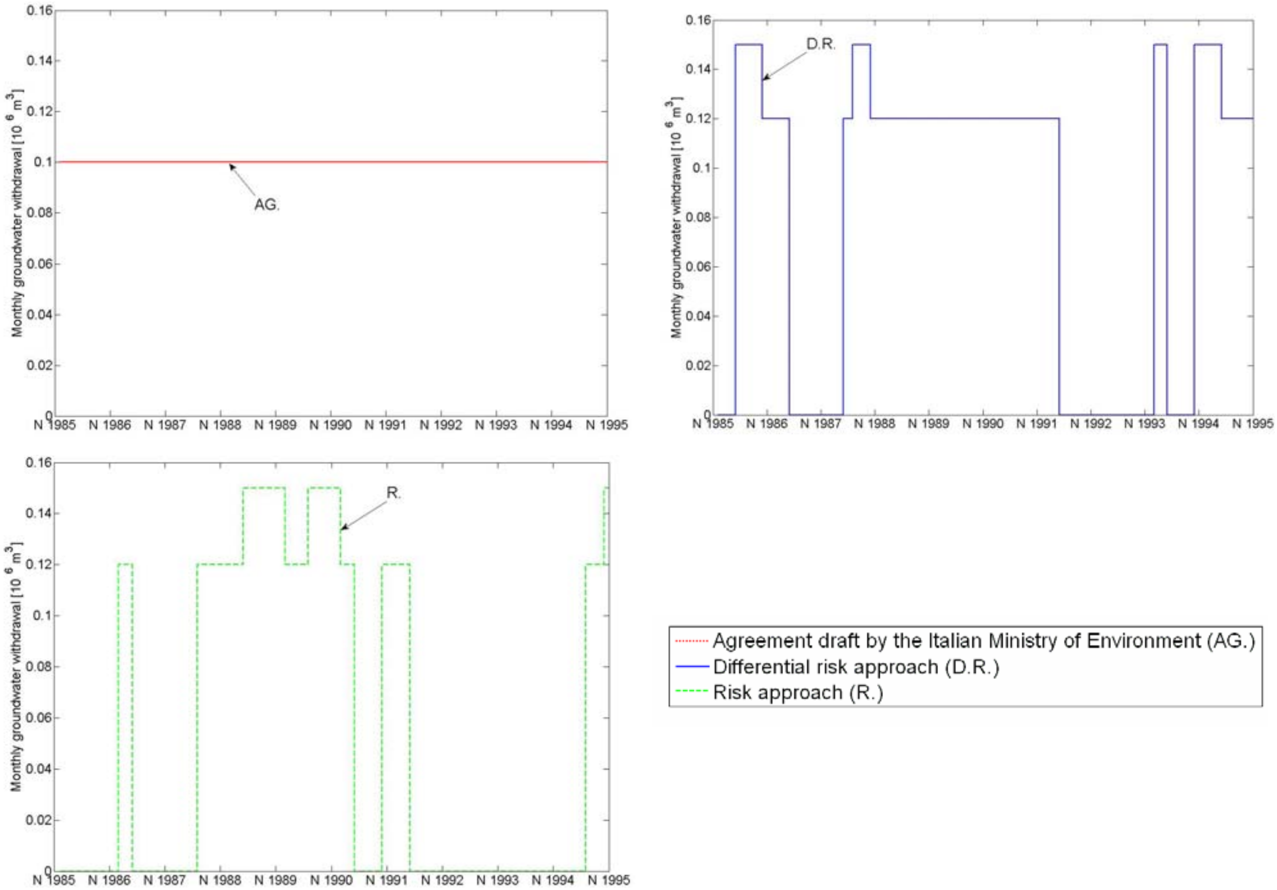


Figure 4 Comparison among monthly groundwater withdrawal considering the agreement draft by the Italian Ministry of Environment (AG.), Risk approach (R.) and Differential Risk approach (D.R.)

In order to analyze the trade-off between reduction of groundwater withdrawal and increased water shortages on not-prioritary water uses an index of the overall performance of the water supply system has been considered, based on the sums of squared shortages computed for each water use.

Indeed, sum of squared shortages index is a reliable measures of the total performance of a water supply system because can be considered as a good proxy variable of the economic losses due to water shortages being the cost function generally well approximated as a non linear function.

For this reason the sum over the three supplied water uses of the sum of squared shortages computed for the whole drought decade (120 months) has been chosen as index of the performance of the water supply system as a whole:

$$\sum_{all\_water\_uses}\left(\sum_{i=1}^{120} short_i^2\right) \tag{8}$$

Figure 5 and Figure 6 show scatter plots of the total groundwater withdrawal during the analyzed drought decade versus the index of the overall performance of the water supply system reported in (8) respectively for R. and D.R.. The AG. labeled points represents the results of the simulation of the water supply system without the activation of the proposed mitigation measures with a constant monthly groundwater withdrawal that sum up to 12 10^6 m^3 for the whole drought decade to which corresponds a value of the overall performance index equal to 7.04 10^6 $[m^3]^2$.

The other points have been obtained by implementing the methodology based on the proposed risk indicator and considering several combinations of amount of groundwater withdrawal corresponding to alert and alarm conditions of the water system with reference to drought. As can be inferred by the analysis of Figure 5 related to R. all the points allow a groundwater withdrawal reduction but to every point corresponds also an increased value of total water shortages suffered by water uses supplied by the system. A different behavior of the curve can be inferred from the analysis of the graph reported in Figure 6 and related to D.R.

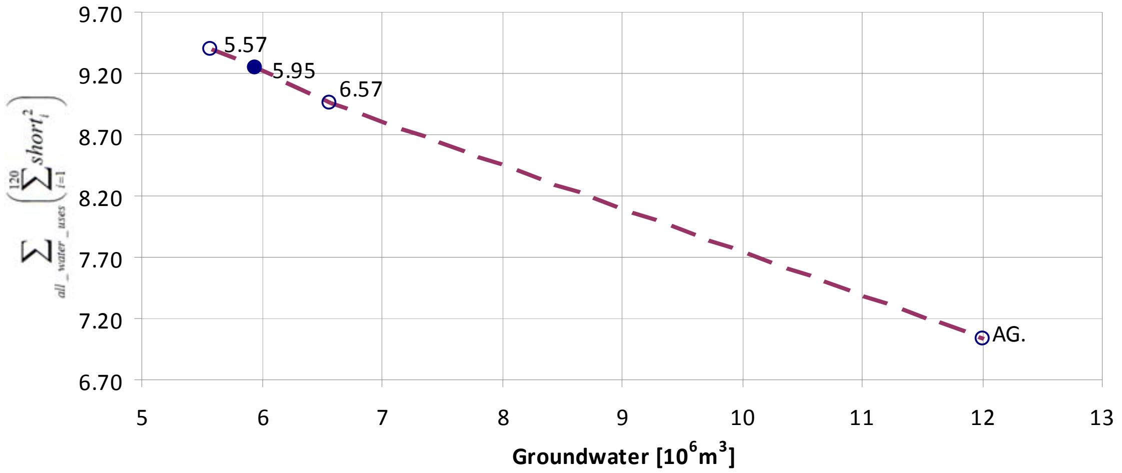


Figure 5 Scatter plot of the index of the overall performance of the water supply system according to risk approach (R.) versus total groundwater withdrawal for the whole drought decade

In particular the scatter plot computed for D.R. (Figure 6) shows that a trade-off between groundwater withdrawal reduction and the index of the overall performance of the water supply system is possible. The filled point in the plot corresponds to a combination of groundwater withdrawals (no withdrawals in normal condition, 0.12 10^6 m^3 in alert and 0.15 10^6 m^3 in alarm conditions) and a sequence of activation of water rationing that allows a 17.25% groundwater saving with reference to AG. over the drought decade and at the same time a reduction of the total summation of squared shortages computed for all the supplied water uses.

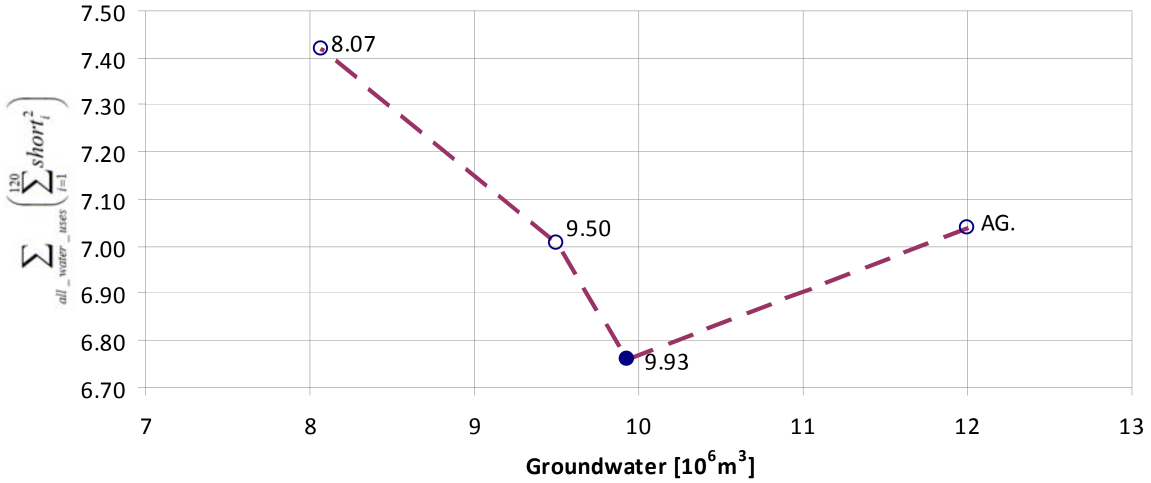


Figure 6 Scatter plot of the index of the overall performance of the water supply system according to differential risk approach (D.R.) versus total groundwater withdrawal for the whole drought decade

A contemporaneous reduction of both groundwater withdrawals and squared water shortages is possible because implementing the proposed methodology with a differential risk approach shortages are redistributed according to a pattern that avoid severe concentrated shortages in favor of mild more frequent shortages. At the same time groundwater withdrawals are activated only during alert and alarm conditions allowing a global water saving over the long time horizon also reducing pumping costs and environmental impacts costs of frequent groundwater withdrawal.

Figure 7 shows a comparison between results obtained applying AG. and D.R. managing policies in terms of probabilities of water shortages classified according to water shortage severity. With reference to municipal use D.R. reduces the probability of water shortages for May, October and November leaving the same probability of shortage of AG. for the remaining months. Probabilities of water shortages for irrigation and industrial water uses are generally incremented implementing the proposed methodology but severity of shortages is significantly reduced as shown by the presence of frequent monthly water shortages belonging to white and green classes.

5. CONCLUSIONS

Management of water supply systems often requires to take decisions using uncertain information. Timely activation of appropriate drought mitigation measures, though potentially leading to significant reduction of droughts most adverse impacts, yet must be done without knowledge of the future evolution of the drought. Thus, a correct approach for managing water supply systems should be based on the assessment of risk of future shortages, considering different managing alternatives.

The methodology presented here has been developed with reference to a water supply system including several water uses and sources, with the aim of supporting the decision about when and how to activate predefined sets of mitigation measures against drought impacts including a more efficient conjunctive use of water. The methodology is based on the assessment, through a Montecarlo simulation, of the risks of future shortages, considering three possible drought management alternatives for the system, namely normal, alert and alarm. Then, according to the values of such risks, the most appropriate set of mitigation measures is triggered. In particular, two approaches have been proposed for triggering management actions, the first based on comparing the risks with fixed thresholds, while the second considering the marginal reduction of risk when switching from one state to another. The application of the methodology to a water supply system in Sicily, including surface water and groundwater sources, and different water uses, indicates that it would enable to improve the performances of the water supply system with reference to the current management, while reducing the overall groundwater withdrawal.

Further research is attempting to extend the formulation of the drought risk indicator, by taking also into account the economic assessment of shortage damages and of the evaluation of the costs of mitigation measures.

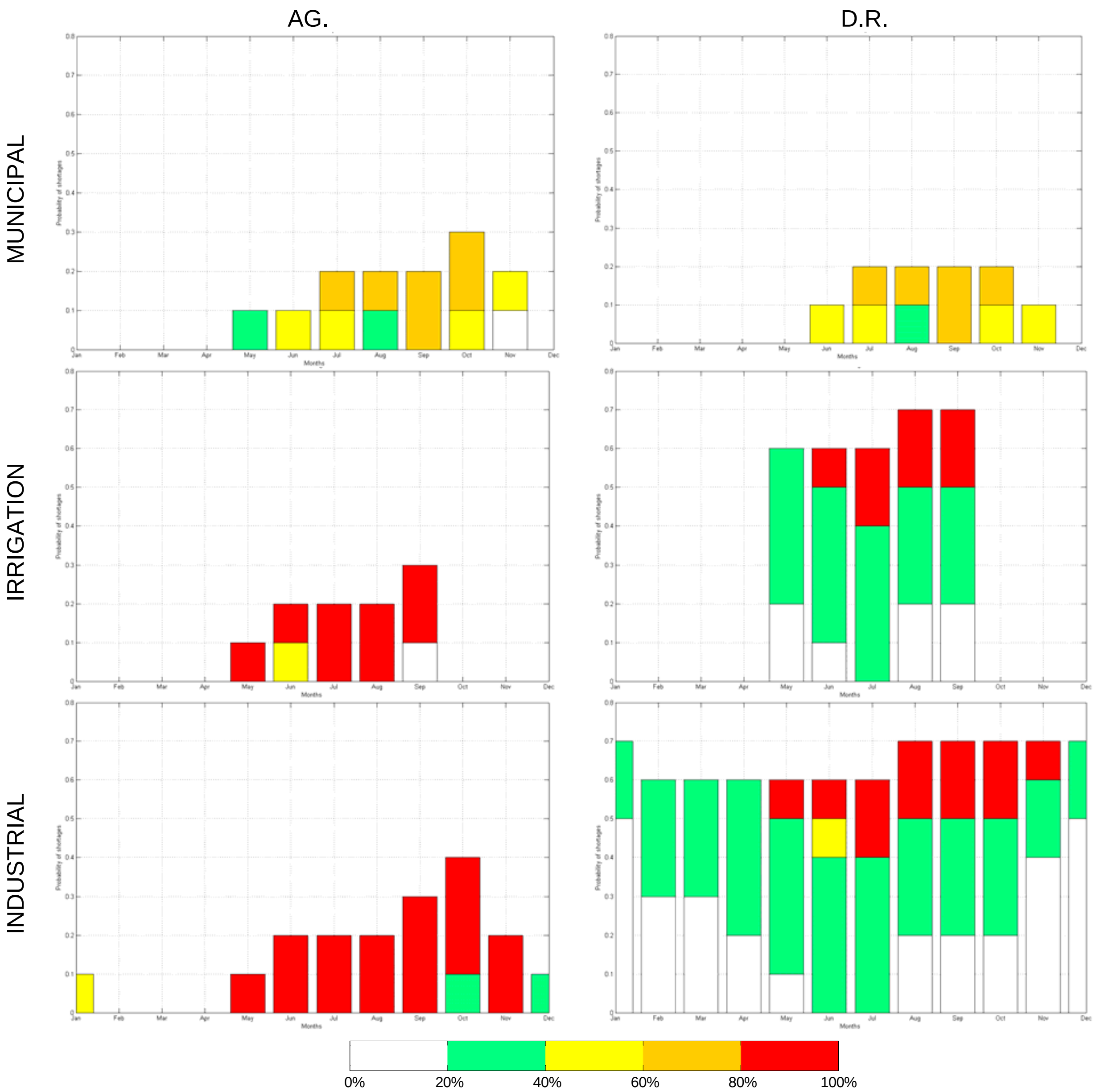


Figure 7 Comparison between results obtained applying AG. and D.R. managing policies in terms of frequency of water shortages classified according to water shortage severity

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