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in

López-Francos A. (ed.).
Drought management: scientific and technological innovations

Zaragoza : CIHEAM
Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 80

2008
pages 251-266

Recent methods and techniques for managing hydrological droughts

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SUMMARY – It is largely recognized that shifting from a reactive to a proactive approach is necessary to face successfully hydrological drought risk. Nonetheless, such an change in drought management requires the support of several methods and techniques that can find application both for planning mitigation actions as well as for implementing the measures. In the paper a planning framework for managing the impacts of hydrological drought divided into strategic, tactical and emergency levels is described, and the main tasks for each planning level are discussed. Furthermore, for each analyzed task, a critical review of recent advances, open issues and perspectives on future developments are illustrated. In particular, characterization, monitoring and forecasting of hydrological droughts are discussed by analyzing new proposed indices, the potential improvements in early drought detection that could derive from the use of aggregated drought indices as well as the role of global climatic indices for increasing the reliability of drought forecasting. Also methods for the assessment of water shortage risks are discussed, either unconditional for strategic planning or conditional for tactical and emergency planning. In the latter cases the role of risk assessment as a tool to trigger the implementation of the planned actions corresponding to different levels of severity of drought is illustrated. Also the role of multicriterion ranking of mitigation alternatives to improve decisions in drought mitigation process is presented.

Key words: Hydrological drought indices, water management, risk analysis, monitoring, multicriterion assessment.

RESUME – *Pour faire face avec succès au risque de la sécheresse hydrologique il faut passer de d'une approche réactive à une approche proactive. Toutefois, cette évolution dans la gestion de la sécheresse exige plusieurs méthodes et techniques qui peutpeuvent être appliquées soit pendant la phase de planification des interventions de mitigation soit pendant la phase d'exécution des mesures. Cet article décrit un tableauschéma de planification pour la gestion des conséquences de la sécheresse hydrologique en distinguant trois niveaux de planification: stratégique, tactique et en cas d'urgence et pour chaque niveau on examine le les principaux instruments qui peutpeuvent être utilisés. Pour chaque instrument analysé, on illustre un compte-rendu des récentesrécents progrès, des questions encore sans réponse et des possibilités de développement à l'avenir. sont illustrés. En particulier, cet article se focalise sur la caractérisation, le monitoragesuivi et la prévision de la sécheresse hydrologique. On analyse les nouveaux indices qui ont été proposés, le possibles progrès dans la perception en avance de la sécheresse qui peut provenir de l'usepar l'utilisation des indices agrégats et en autreaussi bien que le rôle des indicateurs globalesglobaux climatiques pour améliorer la fiabilité de la prévision. Ensuite, on discute sur les méthodes pour évaluer soit le risque inconditionnel de pénuries de l'en eau pour la planification stratégique soit le risque conditionnel pour la planification tactique et en cas d'urgence. Dans le dernier cas, en particulier, on analyse le rôle de l'estimation du risque pour représenter une un seuil pour l'exécution des mesures planifiées en correspondance avec des différents niveaux de gravité de la sécheresse. Enfin, on présente le rôle du classement qui se fonde sur l'analyse multicriteriale des différentes alternatives de mitigation pour améliorer les décisions dans la mitigation de la sècheresse.*

Mots-clés : *Indices de sécheresse hydrologique, gestion de l'eau, analyse du risque, monitorage-suivi, analyse multicritère.*

Introduction

The presentation of the 4th IPCC Report on climatic change (IPCC, 2007) has given new voice to concerns on the priority to be assigned to the adaptations to climatic change for avoiding dramatic water crises affecting a large part of the world population. Many academic and operational groups, with a long standing experience in the field of water resources management (e.g Stockholm International Water Institute and World Water Council), although agreeing on the basis of the precaution principle about the necessity to take into account such a new threat, believe that it represents one of several factors to be included in an integrated approach to multi-faceted water scarcity problems.

At European level a distinction is generally accepted between permanent water scarcity problems, due to unbalance between available water resources and increased demands due to population increase, urbanization and tourism growth and irrigated agriculture enlargement, and temporary water shortage due to drought events (WSDEN, 2007). The experience of last decades demonstrates that the risk of both phenomena is increasing especially in arid and semiarid climatic zones, and an unique general approach, based on the preliminary planning of necessary measures, should be adopted, although different specific measures could be required. Such an approach, generally accepted in the past for permanent scarcity problems, is now gaining large consensus also for coping with drought, perceived as one of the most dangerous natural hazards in terms of economic and social impacts. Therefore, for an effective drought management, the necessity of moving from an emergency management and drought relief to a pro-active and comprehensive approach based on prediction, preparedness and mitigation is largely recognized (Wilhite, 1991; Rossi, 2000). Within such an approach, the use of models and techniques which can improve the decision process for managing drought impacts can be considered as a key element to implement successful policies for avoiding water crises.

The paper presents, within a planning framework of drought risk management, recent advances and open issues regarding characterization and monitoring of hydrological drought, assessment of water shortage risk as well as evaluation of alternative measures. Perspectives on future developments in these fields are also discussed.

Concepts of the hydrological drought risk management

Drought and risk definitions

A comprehensive definition of drought is difficult, since the component of hydrological cycle under investigation, the time scale, the way by which the deviation from the considered "normal condition" is measured as well as the purpose of the analysis can influence the definition of the phenomenon.

From the several reviews of drought definitions (Yevjevich et al.,1978; Rossi et al.,1992; Tate and Gustard,2000) it is evident that "hydrological" drought concept can be more controversial than "meteorological" drought concept. If consensus on meteorological drought can be easily found, defining it as "a temporary severe reduction of precipitation (compared to normal value) extending along a significant period of time over a large region", different definitions derive from a point of view which privileges the situation of reduction of water availability in natural bodies as streams, lakes or aquifers (hydrological drought "strictu sensu") and/or reduction of water availability in all forms of water supply, including the man-made water structures for storage, regulation and conveyance such as reservoirs or groundwater pumping facilities (to be preferably indicated as "water supply drought" or "operational drought").

Here the term hydrological drought is used to indicate water deficit in natural water bodies generated by a reduction in precipitation routed through the land component of hydrological cycle, while "water shortage" is used to describe the water deficit with reference to the demands of a water supply system, which is affected by features of the system, including operation rules.

The concept of risk represents a key issue within a probabilistic approach to drought management. There is no unique, universally accepted definition of risk since different ways of defining and/or computing risk are adopted in various disciplines, according to the objective of the analysis, as well as to the type of event under study.

Despite the differences, the several definitions can be broadly divided into two main categories: risk defined as the probability of an adverse event and risk defined as the expected consequences of an adverse event.

The classical definition of risk, according to statistical hydrology, refers to the probability that a variable X exceeds a given threshold x_0 at least once in n years:

Risk=P[at least 1 year in n years where $X>x_0$]=1-P[$X \leq x_0$ in *n* years]

Assuming that the events are independently and identically distributed, the risk can be computed by the well known formula where the threshold x_0 usually refers to some value of the variable X beyond which damage occurs:

Risk=1-P[$X \leq x_0$]^n

Similarly, in reliability theory, risk is defined as the probability of failure for the system under investigation. More specifically, risk is defined as the probability that the load L (i.e. the external forcing factor) exceeds the resistance R (an intrinsic characteristic of the system), leading to a failure:

Risk=P [L>R]

The second category (risk as expected consequence) includes the definitions developed within the strategies for natural disasters mitigation. In particular, risk has been defined as the expected damages due to a particular natural phenomenon as a function of natural hazard and vulnerability and element at risk by United Nations (UNDRO, 1991). However recently the United Nation-International strategy for disaster reduction (UNISDR, 2004) has adopted a somewhat ambiguous definition that includes two different concepts (risk as probability of harmful consequences or expected losses or damages).

When dealing with water supply systems, risk of drought should be quantified in terms of the economic losses consequent to water shortages for the different uses. Thus, a probabilistic analysis of shortages due to droughts should be first performed, to be followed by the transformation of shortages into economic losses by means of an appropriate loss function. However, it is customary to assume shortages as a proxy of economical losses and therefore concentrate the attention only to the probabilistic features of shortages. In this sense, it is customary to refer to shortage risk assessment.

Hydrological drought risk management process

An effective process for the management of hydrological drought risk is based on a few basic principles. First of all, since drought originates from the variability of meteorological conditions, it can be considered as a natural phenomenon but the severity of drought's impacts depends on the vulnerability of water supply systems and of economical and social sectors as well as on the effectiveness of the adopted mitigation measures. Furthermore a reactive approach based on emergency measures selected after drought consequences are perceived is inadequate and should be replaced by a proactive approach.

The reactive approach identifies the mitigation measures only after the drought has begun and has been perceived as a severe threat. In many cases such an approach is insufficient to reduce water shortages and is often highly inefficient in terms of financial resources. On the other hand, the complexity of drought impacts requires a preventive, anticipatory approach to risk, consisting essentially of two different phases: development of drought management plans and implementation of the identified measures (both before and after a drought event begins).

The proactive approach firstly provides an assessment of water resources availability to meet different demands, then evaluates the water shortage risk through an analysis of the different elements of a water supply system; after the analysis of drought impacts on the different sectors, the actions to be taken into account to reduce vulnerability to drought (long-term measures) and action oriented to mitigate drought impacts are defined within planning documents.

The second phase of proactive approach foresees a continuous monitoring of hydrometeorological variables and of the status of water reserves in order to identify possible water crisis situations and to apply the necessary measures before a real water emergency occurs.

Long-term measures entail a set of structural and non-structural adjustments to an existing water supply system, aimed at protecting the system from adverse effects of future drought by reducing its vulnerability to drought as risk of water shortage. Short-term measures refer to the capability of facing an ongoing drought. Such measures include actions planned before a drought begins (within contingency plan), which are implemented when the monitoring system indicates that a alarm situation is occurring.

The choice of the mix of long-term and short-term mitigation measures to cope with drought is a decision that requires to take into account the different points of view of involved stakeholders also through transparency in information and public participation.

Within the planning framework to manage hydrological drought risk different tools can be identified.

In particular, as reported in Figure 1, the general framework comprises three different management levels (Strategic, Tactical and Emergency) to which correspond different plans and relative actions. To be effective the proposed planning framework should be supported by adequate tools able to characterize and monitor drought, to assess water shortage risk and to evaluate mitigation measures through multicriteria analysis.

In the following paragraphs recent advances and open issues of the identified tools will be discussed.

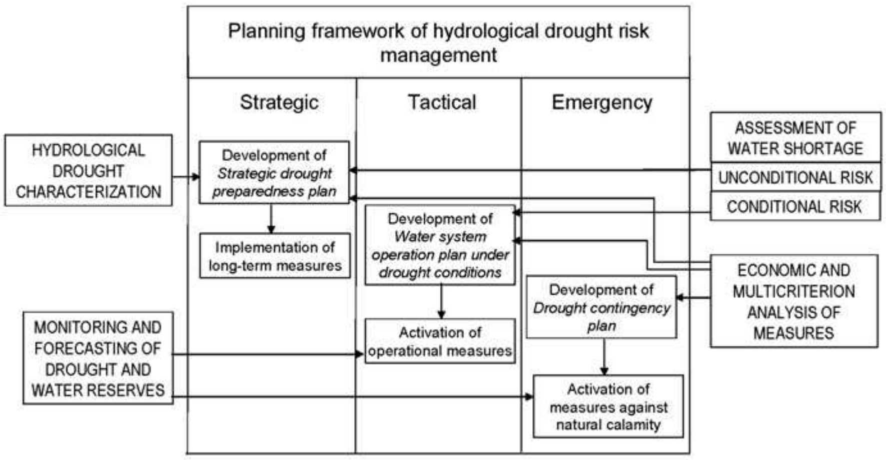

Fig. 1. Tools for hydrological drought risk management process.

Planning framework of hydrological drought risk management

Recent advances

Although a clearly defined planning framework for hydrological drought risk management is still lacking at European level, some recent initiatives and indications proposed on the basis of the Water Framework Directive 2000/60 (WFD), can be considered positive advancements.

The WFD main goal is to reach a good ecological status in water bodies and, except for groundwater, does not address quantitative water issues. However WFD marginally deals with drought and water scarcity issues, indicating the mitigation of drought as one of its objectives (article 1.e) and considering "prolonged droughts" as "force majeure" events that enable to temporary derogations to environmental prescriptions in terms of delay or less stringent quality objectives (article 4.6). On the basis of the WFD a Water Scarcity Group (WSG), established in 2003 at the Meeting of Water Directors of the EU, prepared a document dealing with water scarcity and drought issues at European level and proposing that a Drought Management Plan can be included as a sub-plan of the River basin Management Plan. This is in agreement with the article 13.5 of WFD that states that such plan can be supplemented by management plans for sub-basin, sector, issue, or water type, to deal with particular aspects of water management.

General indications provided at European level concerning steering, coordinating and controlling integrated and sustainable management of available water resources both in normal and drought conditions are being transferred, also with some difficulties, in the national legislations and practises of several countries of the EU.

Some governments have started a drought mitigation process based on three level of planning: drought preparedness in water resources planning (Strategic planning), drought management in water supply systems operation (Tactical planning), mitigation actions and damage recovery in extreme droughts declared as natural calamity (Emergency planning).

Open Issues

Although there is a general consensus on the need of planning for droughts, yet differences exist in the way such planning is carried out in different countries. In particular, at European level some of the main open issues regarding the planning framework of hydrological drought risk management are:

(i) definition of the territorial unit to be considered for different levels of planning and the corresponding responsible institutions;

(ii) criteria for the allocation of water during hydrological drought events;

(iii) selection of the policy to be adopted by Governments to recover from an extreme drought event declared as natural calamity.

A possible sharing of the responsibilities for planning and implementation of drought preparedness and mitigation actions attributes strategic plan for drought preparedness to River Basin Authority, tactical plan for drought water resource management under drought conditions to management Agencies (not necessarily coincident with Basin Authority) and drought emergency plan to Region or National Civil Protection Organizations. However, this sharing of responsibilities, is not applicable to all countries since the general legal framework of each country and/or the difficulties in coordination of actions among different levels of government could promote other schemes in the development of plans and activation of planned interventions.

A common accepted view on the allocation of water resources among different off-stream uses during hydrological droughts gives priority to municipal use over irrigation and industrial uses. On the other hand the issue of sharing river flows between in-stream flow requirements and consumptive needs satisfied by derived flows is still open and consolidated procedures to evaluate amount of water to be allocated to environmental use (both for water quality standard achievements and river ecosystems conservation) during hydrological drought are not available.

The policy to be adopted by Governments to recover damage and support stakeholders stricken by extreme drought event declared as natural calamity presents two main alternatives, namely, recovery from damages can be financially supported through public solidarity funds or compulsory private insurance can be imposed for agricultural and industrial users. For example the Government of Australia moved from the public reimbursment of drought damage within a disaster recovery perspective to a risk management approach through the National Drought Policy (1992) which considers drought as one of the ordinary factors of risk for agricultural activity in the context of a variable climate.

Perspectives on future developments

Future developments on drought management will have to take into account technological innovations both for the supply and the demand side. For instance, the increasing use of desalination especially in coastal areas can potentially lead to reduce the susceptibility of municipal water supply to drought, due to its less dependence on conventional water whose availability is subject to climatic variability. Such reduced pressure on the use of conventional sources for municipal supply will lead to an apparent benefit from an environmental point of view (e.g. reduced withdrawals from coastal aquifers), but with an increased cost in terms of energy. Technological innovations will certainly contribute to a more efficient desalination in terms of energy consumption, leading to a more widespread use, thus requiring to review existing drought management plans, in order to take into account new sources of water.

Water saving is another aspect that will influence the amount of the water demands and therefore will have an impact on future drought management policies. An increased sensibility toward water saving can, on the one hand, increase the willingness of water users to reduce their consumption during drought periods. At the same time however one can expect that the reduction of the demands during normal periods (in theory up to the point where all unnecessary uses are already curtailed), will obviously reduce the margin of water that can be saved during drought periods, thus making water use restrictions less effective within a larger mitigation strategy.

Hydrological drought characterization and monitoring

Recent advances

Several indices have been proposed to characterize and monitor meteorological or hydrological droughts, among which the Palmer index (Palmer, 1965) is perhaps one of the most widespread.

Another index that has found great popularity is the Standardized Precipitation Index (SPI) proposed by McKee *et al.* (1993), to monitor droughts at different time scales. More recently, the Reconnaissance Drought Index (RDI) has been proposed by Tsakiris *et al.* (2007), based on the ratio of precipitation over a time period to the corresponding evapotranspiration. Indices are generally computed at given sites or by using areal averages of the meteorological variables. An improved characterization of droughts at regional scale can be achieved making use of remote sensing based indices that enable a description of the spatial features of droughts and of their evolution in time.

Generally speaking, indices assess drought conditions by using some threshold values for distinguishing different drought categories; also if these thresholds are defined in empirical or probabilistic way, they try to represent the expected impacts corresponding to each level of severity. The thresholds, distinguishing the levels of drought severity are oriented to determine when drought responses should be activated and concluded.

However, most of the proposed indices do not enable a probabilistic assessment of drought characteristics. On the other hand, in the last decade, there has been a renewed interest in literature in analysing droughts from a probabilistic perspective, either by fitting probability distribution functions to historical drought events, by deriving analytically probabilities and/or return periods of drought features by using stochastic properties of the basic variable and/or by data generation (Cancelliere *et al.,* 1998; Fernandez and Salas,1999; Bonaccorso *et al.,* 2003, Cancelliere and Salas, 2004). Interestingly enough, most of the recently developed applications are based on the not-so-recent drought identification method known in literature as "run theory" (Yevjevich,1967), which uses a fixed threshold on a time series of the chosen variable to determine duration and cumulative deficit (or intensity) of negative runs. The method enables an objective identification and characterization of droughts, provided the selected threshold is representative of normal conditions. In an effort to remove the influence of the threshold on the identified droughts, the Drought Frequency Index (Gonzales and Valdes, 2006) has been proposed, which is based on the concept of persistent deviations from normal. Also, paleo-climatology approaches, such as tree-ring based data reconstruction, have been the subject of some studies (Woodhouse and Lukas, 2006; Meko *et al.,* 2007; Li *et al.,* 2007), in order to overcome the difficulties arising from the limited number of droughts that can generally be identified in observed records of hydrometeorological variables, or to investigate changes in climate and their effects on societies (Benson *et al.,* 2007).

In general terms, an effective response to drought depends on the early perception of droughts through an accurate monitoring of meteorological and hydrological variables as well as water resources availability. As a consequence, the indices to be used within a drought monitoring system have to satisfy several requisites, among which:

(i) representing the different features of the complex interrelation between meteorological and hydrological components of a significant reduction of water availability;

(ii) making use of real-time easily available hydro-meteorological data;

(iii) being able to describe drought conditions even in its early stage;

(iv) providing comparability of drought events both in time and space;

(v) describing in some way drought impacts;

(vi) assessing in a clear way the severity of the current drought conditions as triggers to support decision makers to activate drought mitigation action.

Table I summarizes a comparison among the most consolidated indices (Palmer, SPI) and a few new indices, as RDI (Reconnaissance Drought Index) and DFI (Drought Frequency Index), oriented to explore strengths and weaknesses, spatial comparability, relevance as proxy of critical impacts and suitability for a monitoring system.

Table 1. Comparison among some of the most common drought indices

Index	Strength	Weakness	Spatial comparability	Relevance for impact assessment	Suitability for monitoring
PHDI – Palmer Hydrological Drought Index (Palmer, 1965)	- Detailed estimate of hydrological drought based on soil moisture balance	- Classes of drought severity not consistent in terms of probability of occurrence	- Poor since empirical parameters estimated for arid regions of USA	- Good description of agricultural impacts	- Large use in monitoring systems (although it underestimates drought in wet regions)
SPI – Standardized Precipitation Index (McKee *et al.*, 1993)	- Simple computation and easy interpretation - Drought categories based on probability	- Severity of drought events sensitive to aggregation time scale	- Very high for fixed time-scale. - Difficulties to compare events of different duration	- Good description of severity of generic impacts.	- Very large use for early warning of drought
RDI – Reconnaissance Drought Index (Tsakiris *et al.*, 2006)	- Estimate based on precipitation and potential evapotranspiration PET. - Able to analyse climatic change	- Necessity of data for computing PET. - Being variability of PET lower than precipitation, drought description very similar to SPI.	- Very high for fixed time-scale	- Good description of agricultural impacts	- Use yet limited
DFI – Drought Frequency Index (Gonzalez and Valdes, 2006)	- Asymptotic estimation of return period considering persistent deviation from normal. - Slightly sensitive to the selected threshold	- Complex computation under the hypothesis of randomness and time independence of considered variable	- Very high since index is slightly sensitive to threshold, time-scale and characteristic (i.e. duration, cumulative deficit)	- Depending on the selected variable. - Poor relevance since drought characteristics not directly representative of impacts.	- Difficult application since index is oriented to probabilistic characterization of drought

Besides providing information on current drought conditions, a drought monitoring system should also give indications on the probable evolution of the phenomenon in the future. Several authors have proposed methods to forecast or to assess the probable evolution of Palmer index (Rao and Padmanabhan, 1984; Kim and Valdes, 2003; Karl *et al.,* 1986; Cancelliere *et al.,* 1996; Lohani *et al.,* 1998) or SPI (Moreira *et al.,* 2006; Cancelliere *et al.,* 2005; Bordi *et al.* 2005; Cancelliere *et al.,* 2007).

Despite such efforts, forecasting when a drought is likely to begin or to come to an end is still a difficult task. Recently, important progress is being made in relation to the possibilities of using information provided by large-scale climatic indices, such as the North Atlantic Oscillation (NAO), as a support to drought forecasting. Influence of NAO index on precipitation in western Europe and the Mediterranean basin has been observed by several authors (Hurrell, 1995; Qian *et al.,* 2000, Goodess and Jones, 2002) Thus, including the information from such an index within a forecasting model, can potentially lead to an improved forecasting ability, as well as to a longer time horizon of forecasting (Di Mauro *et al.,* 2008).

Open issues

Despite each index describes a specific feature of drought, often there is the need to merge the information from several indices into one value representative of the different features of the natural hydrological phenomenon and/or of the vulnerability of the water supply system to drought. However, due to the complexity of the problem, combining different indices into one value is not trivial since:

(i) most indices are standardized in different ways, or sometimes not standardized at all:

(ii) each index generally represents drought conditions affecting different uses and/or features of the system;

(iii) the classification of drought severities is affected by a great deal of subjectivity since generally drought class limits for different indices do not correspond to the same occurrence probability.

Different solutions to the problem have been proposed worldwide for different regions. Keyantash and Dracup, (2004) use an Aggregate Drought Index (ADI) that considers all relevant variables of hydrological cycle (precipitation, streamflow, evapotranspiration, soil moisture) including also water stored in water reservoirs and considering different climate divisions of the area under study. In order to calculate a single ADI value for each month, Principal Components Analysis is carried out and results are deseasonalized to extract dominant hydrologic signals.

Steinemann and Cavalcanti (2006) analyze statistical, temporal and spatial consistency and specificity of drought indices based on precipitation, streamflows, reservoirs' storages and groundwaters for combining indicators and triggers to be used within drought plans. These triggers can be selected according to three methodologies: most severe drought level; majority of drought levels; IN triggers and OUT triggers. The first is based on the most severe condition for each month among a set of indicators. The majority of drought levels approach refers to drought level at which 50% or more of the indicators are equally or more severe. Finally the last method uses the IN triggers to move from a less severe to a more severe drought level seeking early actions in invoking drought restrictions, whereas OUT triggers are used to move from a more severe level to a less severe seeking more conservative actions in revoking drought restrictions.

Despite the number of drought indices currently adopted by several monitoring systems in the water supply systems management, "ad hoc" indices are often required. They should represent directly the status of water availability in the system (e.g. water stored in reservoirs or groundwater table levels) with respect to current and short-term future water demands in order to support decision makers to trigger mitigation measures oriented to avoid severe failure of the water supply system. For instance Estrela *et al.,* (2006) propose dimensionless indicators for the Jucar basin in Spain for each areas in which the basin can be divided according to the main source for supplying different uses. The indicators, oriented to the operational aspects of drought management are expressed in a dimensionless and deseasonalized form assuming two different linear relationships one for values less than historical average and the second for values greater than the historical average.

Perspectives on future developments

Future developments on drought characterization and monitoring will have to consider that drought condition of a given area depicted by drought indexes not always reflect the actual risk of water shortage which should be evaluated also on the basis of the actual reliability of the water supply systems. The use of specific indicators identified for the particular water supply system under study in order to catch specific features of the system should be improved. The specific indicators have to take into account both the reliability of the source (groundwater, river flows, reservoirs) and the vulnerability of the demand (municipal, agriculture, environment).

In the future, developments on the definition of the spatial scale to be preferred for drought monitoring, are expected. Although in many countries the solution of a national drought monitoring centre could appear convenient to link meteorological and hydrological services responsible for data acquisition, in other countries a specific set of indices are required within the river basin or the administrative boundaries (i.e. Basin authority or Region) especially where the monitoring is directly oriented to represent water shortage risk in the main sources of the water supply system.

Also the possibility to forecast droughts at seasonal scale will receive increasing attention in the future, due to its potential to reduce dramatically the uncertainties related to drought management. Important advancements in this directions are to be expected as progresses are made in relation to the better understanding of global atmospheric circulation and of its effects at smaller scales such as regional or basin. In this context, the use of global climatic indices can contribute to improve drought forecasting reliability.

Assessment of water shortage risk and evaluation of mitigation measures

Recent advances

Traditionally, characterization of the shortages in a water supply system has been carried out by means of a set of performance indices, attempting to capture different aspects related to concepts such as reliability, resiliency and vulnerability (Hashimoto *et al.,* 1982). Indeed, stochastic nature of inflows, high interconnection between the different components of the system, presence of many sometimes conflicting demands, definition of the elements at risk, uncertainty related to the actual impacts of droughts, make the risk assessment of a water supply system a problem that is better faced through a set of several indices and/or by analyzing the probabilities of shortages of different entities.

More recently procedures for risk assessment of failure due to drought in water supply through simulation and computation of failure probability for comparing drought management alternatives have been proposed and applied (Nicolosi *et al.,* 2007; Westphal *et al.* 2007)

Assessment of shortage risk is required either at the planning stage or during the operation of a given system. For instance, with reference to water supply system planning, risk assessment enables to quantify and compare the risk associated with different planning alternatives, generally on a long term basis. On the other hand, during the operation of the system, short term drought risk assessment can be carried out in order to compare and define alternative mitigation measures, on the basis of the consequent risk during a short time period in the future.

The two approaches differ, not only with regard to the objective of the analysis and to the different lengths of the time horizons, but in relation to the way the probabilistic assessment is carried out. In the first case, the assessment is unconditional and is oriented to the evaluation of the probability of different levels of shortage during the whole time horizon chosen for the planning (30-40 years) and can be considered unconditional since initial conditions of the system are almost irrelevant on the behaviour for a such time horizon. Its main objectives are the evaluation and the selection of preferred drought mitigation alternatives through the simulation of the system behaviour by using generated series. The risk is evaluated in terms of a synthetic assessment of failure based on the analysis of the satisfaction of consumptive demands (both in time and volume), as well as of meeting some specified objectives such as the satisfaction of ecological requirements.

The short term risk assessment, on the other hand, is generally conditional, in the sense that the initial state/conditions of the system have to be strongly taken into account in the evaluation and, for this reason, the procedure must be repeated as new information becomes available. Furthermore, the assessment is generally oriented to estimating the level of shortage at a specific time in the immediate future (2-3 years).

Both assessments can be carried out efficiently making use of Montecarlo simulation of the system, that enables to take into account implicitly the stochasticity of hydrological inputs that combined with the intrinsic features of the system will lead to the risk of shortages. The basic idea behind Montecarlo simulation is to carry out a large number of simulations of the system under study using synthetically generated hydrological series. Each series is generated by an appropriate stochastic model able to reproduce the main statistical characteristics of the historical observations and therefore can be considered as one of the possible series that may occur in the future. Thus, by statistically analyzing the results (e.g. water shortages) of the several simulations, one may infer probabilistic information about the behaviour of the system under study.

In Figure 2 a scheme of the Montecarlo simulation approach for a water supply system is depicted.

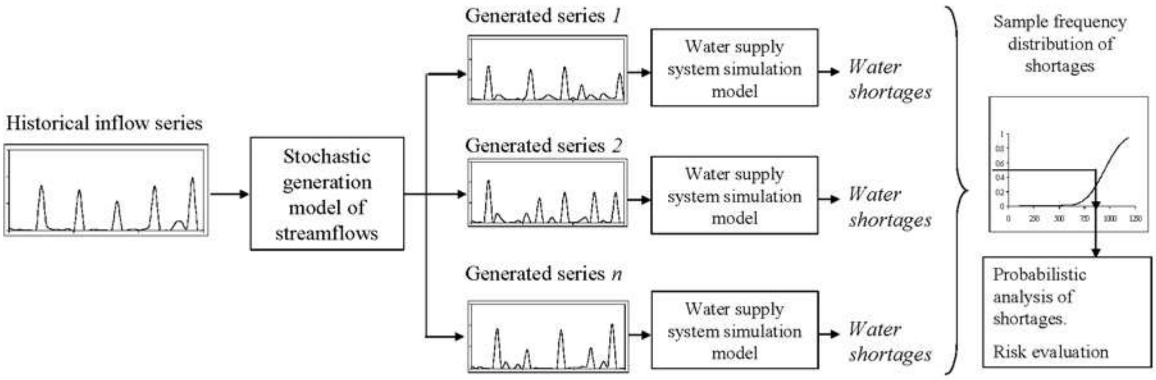

Fig. 2. Montecarlo simulation approach.

Open issues

The output of Montecarlo simulation of a water supply system consists in several series of storage levels in reservoirs, releases to the demands, downstream releases for ecological purposes. Thus, the need arises to describe output of water supply systems simulation in order to provide decision makers with clear and comprehensive information to be used within the decision process regarding the course of actions to be implemented.

Analysis of such results therefore mustmay be carried out by means of indices able to capture different features of the analyzed series, for example:

(i) Water supply system performance indices (reliability, resilience and vulnerability);

(ii) Histogram of monthly and yearly frequencies of shortages either for consumptive demands and ecological requirements such as in-stream flow or target storages in reservoirs;

(iii) Return period of annual shortages exceeding a given value.

As an example, in Fig. 3 histogram of frequencies of shortages are shown with reference to a water supply system. In particular, each color bar represents the frequency of shortages expressed as a percent of the demand (0-20%, >20%-40%, >40%-60%, >60%-80%, >80%-100%) without or with the implementation of a given set of mitigation measures. This representation gives information about the overall monthly probability of shortages and their distribution among the classes for different uses supplied by the water supply system under study, thus providing synthetic indications about the stochastic features of shortages and the effectiveness of a proposed set of mitigation measures.

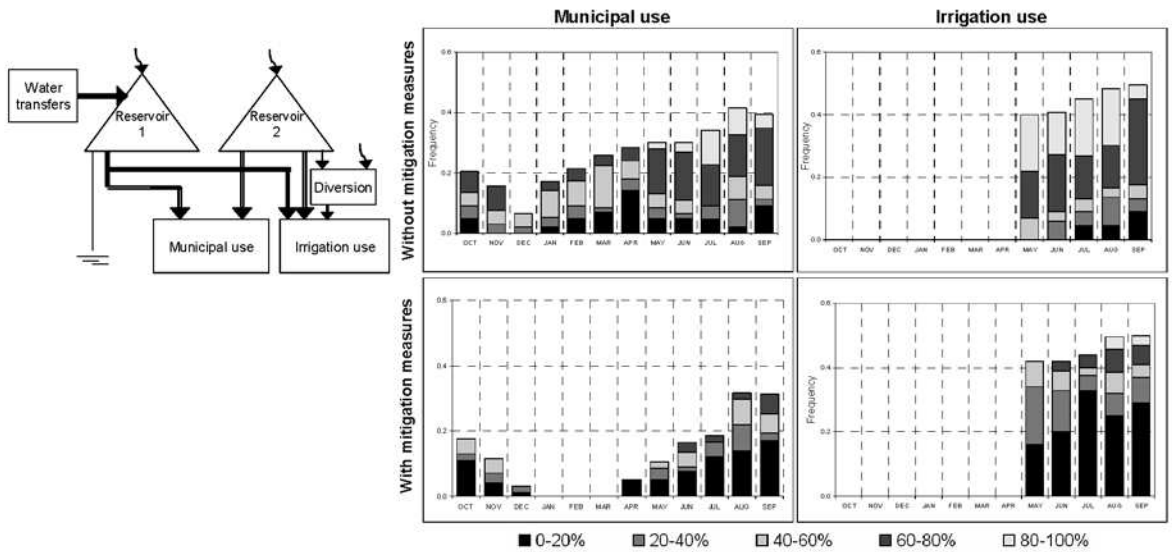

Fig. 3. Histogram of monthly frequencies of shortages for municipal and irrigation use without and with drought mitigation measures.

However further improvements are required to describe output of water supply systems simulation in order to provide decision makers with clear and comprehensive information to be used within the decision process regarding the course of actions to be implemented.

Due to the variety of drought impacts and in particular to the difficulty of assessing environmental and social impacts, an analysis purely based on the mentioned indices/graphs does may not seem be adequate in some cases to support the real decisional process. Application of a multi-criteria analysis may overcome the above difficulties because of its ability to take into account the points of view of different stakeholders on the different alternatives (Rossi *et al.,* 2005).

This requires preliminary selection of the multicriteria technique, the identification of the alternatives, the definition of the criteria against which to compare them, and the elicitation of the stakeholder preferences.

Identification of sets of alternatives is not easy. Although, long-term interventions could be more appropriate in a system for which emergency measures are frequently applied, on the other hand, if the risk of drought damages during the planning period is low or moderate, the best strategy can be to rely upon the short-term measures.

Definition of criteria against which compare the proposed set of mitigation measures and elicitation of stakeholders preferences can be carried out through several methodologies (ELECTRE methods, Compromise programming, NAIADE) in the attempt to take into account both the operational as well as the economical, social, and environmental standpoint. Alternatives can be ranked and coalition groups can be identified in order to get an overall convenient set of mitigation measures both at long and short time horizon.

The choice of the preferable method for a multicriteria assessment is yet an open issue.

Perspectives on future developments

Planning framework

Drought management has received a great deal of attention in the past decades. Nonetheless, it can be expected that increasing pressures on water resources due to the growth of the demand, reduction of water availability due also to quality problems, as well as possible changes in the climate will worsen the effects of droughts, thus fostering new advancements in searching for planning mitigation strategies.

In particular, it can be expected that the gaining importance of the ecocentric view with respect to the anthropocentric paradigma that yet dominates the complex relationship between human society and environment, will lead to orient future water policies to environmental protection. Environment oriented policies will give more emphasis on the environmental impacts of drought and drought mitigation alternatives, at the cost of less effective mitigation from the purely economical point of view. In this sense, the use of some type of multicriterion technique, taking into account besides economical, also social and environmental criteria is expected to become an important tool to support decisions.

Furthermore future developments on drought management will have to take into account technological innovations both for the supply and the demand side. For instance, the increasing use of desalination especially in coastal areas can potentially lead to reduce the susceptibility of municipal water supply to drought, due to its less dependence on conventional water whose availability is subject to climatic variability. Such reduced pressure on the use of conventional sources for municipal supply will lead to an apparent benefit from an environmental point of view (e.g. reduced withdrawals from coastal aquifers), but with an increased cost in terms of energy. Technological innovations will certainly contribute to a more efficient desalination in terms of energy consumption, leading to a more widespread use, thus requiring to review existing drought management plans, in order to take into account new sources of water.

Water saving is another aspect that will have an impact on future drought management policies. An increased sensibility toward water saving can, on the one hand, increase the willingness of water users to reduce their consumption during drought periods. At the same time however one can expect that the reduction of the demands during normal periods (in theory up to the point where all unnecessary uses are already curtailed), will obviously reduce the margin of water that can be saved during drought periods, thus making water use restrictions less effective within a larger mitigation strategy.

Characterization and monitoring of drought

Future developments on drought and monitoring have to consider that drought condition of a given area depicted by drought indexes not always reflect the actual risk of water shortage which should be evaluated also on the basis of the actual reliability of the water supply systems. The use of specific indicators identified for the particular water supply system under study in order to catch a specific feature of the system should be improved. The specific indicators have to take into account both the reliability of the source (groundwater, river flows, reservoirs) and the vulnerability of the demand (municipal, agriculture, environment).

In the future, developments on the definition of the spatial scale to be preferred for drought monitoring, are expected. Although in many countries the solution of a national drought monitoring centre could appear convenient to link meteorological and hydrological services responsible for data acquisition, in other countries a specific set of indices are required within the river basin or the administrative boundaries (i.e. Basin authority or Region) especially where the monitoring is directly oriented to represent water shortage risk in the main sources of the water supply system.

Also the possibility to forecast droughts at seasonal scale will receive increasing attention in the future, due to its potential to reduce dramatically the uncertainties related to drought management. Important advancements in this directions are to be expected as progresses are made in relation to the better understanding of global atmospheric circulation and of its effects at smaller scales such as regional or basin. In this context, the use of global climatic indices can contribute to improve drought forecasting reliability.

Risk assessment

The development of specific operational plans to manage water shortage risk at water supply system scale, to be included within a more general planning framework, will require the definition of appropriate indicators to be used as triggers to activate pre-defined set of mitigation measures.

Triggers can be seen as threshold values of indicators based on risk assessment that determine the timing and level of drought responses associated with the state of the system related to the drought conditions. Drought responses to these conditions should include both strategic long-term actions, usually implemented before, during and after a drought and tactical short-term actions, usually to be implemented during a drought. Risk based triggers could facilitate the linking of drought conditions with drought responses.

Water shortage risk should be included as one of the criteria along with economic, environmental or social based ones, within a more general procedure for the selection of the best mix of strategic and tactical mitigation measures.

A further future perspective is the use of water shortage risk assessment to foster the communication of information by water managers in order to raise public awareness on the real condition of a community with respect to current and short-term foreseeable water shortage conditions. Water shortage risk assessment should provide the community with a clear indication of the probability of occurrence of worse water shortage conditions if mitigation measures are not carried out. Furthermore current drought conditions can be better understood by public through the comparison with past droughts whose impacts are still remembered.

Final remarks

Drought management has received a great deal of attention in the past decades. Nonetheless, it can be expected that reduction of water availability due also to quality problems, as well as possible changes in the climate will worsen the effects of droughts, thus fostering new advancements in searching for planning mitigation strategies.

On the other hand, the gaining importance of the ecocentric view with respect to the anthropocentric paradigm that yet dominates the complex relationship between human society and environment, will lead to orient future water policies toward environmental protection placing more emphasis on the environmental impacts of drought and drought mitigation alternatives, at the cost of less effective mitigation from the purely economical point of view. It can be expected that such a paradigm shift will contribute to a more efficient use of available resources reducing vulnerability of water supply systems to drought.

Acknowledgments

Many of the ideas here presented derive from the knowledge gained in the last decade as a result of the participations to some international projects, Inco-Med WAMME (ICA3-CT-1999-00014), Interreg IIIB SEDEMED, MEDA-Medroplan (ME8/AIDCO/2001/0515/59770-P027), Archimed-PRODIM (A.1.009) as well as national project PON Aquatec (1188/2002_12934). The several researchers and water managers who have collaborated to these challenging projects with their valuable and experience-based suggestions are gratefully acknowledged.

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