Water Resour Manage (2007) 21:873–882
DOI 10.1007/s11269-006-9086-3

Linking Drought Indicators to Policy Actions in the Tagus Basin Drought Management Plan

Luis Garrote · Francisco Martin-Carrasco · Francisco Flores-Montoya · Ana Iglesias

Received: 30 January 2006 / Accepted: 31 August 2006 /
Published online: 8 December 2006

Abstract One crucial aspect of drought management plans is to establish a link between basin drought state and management actions. Basin state is described by a drought indicator system that includes variables like precipitation, streamflow, reservoir inflow, reservoir storage and groundwater piezometric levels. Basin policy consists on a catalogue of management actions, ranging from enforcing demand reduction strategies to establishing priority of users to allocate scarce water or approving emergency works. In this paper, the methodology applied in the Tagus Basin Drought Management Plan to link operational drought indicators to policy actions in regulated water supply systems is presented. The methodology is based on the evaluation of the probability of not being able to satisfy system demands for a given time horizon. A simplified model of every water resources system in the basin was built to evaluate the threshold of reservoir volume that is required to overcome the drought situation without deficit. For each reservoir level, a set of policy actions is proposed with the goal of guaranteeing essential demands during drought conditions. The methodology was validated with a simulation of system behavior for 60 years of historic streamflow series, finding acceptable results in most systems.

Key words drought management · drought indicators · water resources · water resources systems · Tagus river

L. Garrote (✉) · F. Martin-Carrasco
Department of Civil Engineering: Hydraulics and Energetics, Universidad Politécnica de Madrid, ETSI Caminos. c/ Prof. Aranguren s/n 28040 Madrid, Spain
e-mail: garrote@caminos.upm.es

F. Martin-Carrasco
e-mail: fmarcar@ciccp.es

F. Flores-Montoya
Public Works Council, Ministerio de Fomento, c/ Fruela, 8 28011 Madrid, Spain
e-mail: fjflores@fomento.es

A. Iglesias
Department of Agricultural Economics and Social Sciences, Universidad Politécnica de Madrid, Av. Complutense s/n, 28040 Madrid, Spain

1 Drought Management Plans in the Tagus Basin

The Tagus basin is located in the central part of the Iberian Peninsula. The main river runs on east–west direction, with a contributing area of 83,678 km^2, of which 55,870 km^2 are located in Spain and the rest in Portugal. The administrative body that is responsible for providing public service regarding water management in the basin is the Basin Authority (Confederación Hidrogáfica del Tajo), with competence on inland water and groundwater.

Institutional responses to hydrological drought or water scarcity in the Tagus Basin can be classified in two categories: proactive and reactive. Proactive measures were defined in the Tagus Basin Water Plan, approved by Royal Decree in 1998, and are in permanent progress. It is expected that the implementation of the Water Plan will improve the reliability of all systems through a set of structural and non-structural measures, thus reducing their vulnerability to drought. However, these measures may not eliminate completely the risks associated to droughts, especially in the case of droughts more severe than those registered in the historic record. Reactive measures are programmed for this contingency. Reactive measures are adopted in drought periods to compensate for water scarcity within the existing framework of water resources, demands and infrastructure in the basin.

Under the traditional approach, the Reservoir Release Commission is in charge of defining measures to react to the drought situation. These measures are usually drafted and decided by water users associations under the guidance of the Water Administration. In general, these reactive responses are specific of drought periods, and are discontinued when the drought is over.

Under water scarcity conditions, management can be very difficult due to the conflict of interests among users. In a scarcity situation there is not enough water to satisfy all users' needs, so certain users must give up their legal rights to use water in favor of other uses of greater priority. The conditions to implement these restrictions of legal rights are frequently the focus of heated arguments, and it is difficult to find a solution that is equally satisfying for all users. If measures are not agreed in advance, users may not acknowledge the severity of the problem, and it will be difficult to win their support for demand management measures.

For these reasons, the Basin Authority is currently developing a drought management plan, in which provisions are made to anticipate conflicts and agree on a solution in advance, without the additional pressure imposed by the developing drought. Plans made in advance may provide the time framework to discuss drought risk among those involved and reach an agreement on the required actions to minimize adverse effects.

The elaboration of the drought management plan is the result of a complex process in which user participation is encouraged and stimulated. Once the plan is drafted, it is submitted to public scrutiny, and concerned individuals and social or political groups can make allegations that are discussed and negotiated in the Water Council, where a majority vote is required for acceptance. If the drafted plan obtains a favorable vote, it is approved by Royal Decree, and is legally binding to all stakeholders.

The process of plan discussion and negotiation is very important, since consensus is a major goal to achieve before the plan is operational. In this context, it is important that the rationale behind the measures proposed in the plan can be understood by all stakeholders that might be affected by them, and therefore, special emphasis has been placed on developing a methodology to establish an objective link between quantitative drought indicators and concrete measures. The methodology involves a comprehensive analysis of alternative policies and an objective procedure to plan the ordered implementation of management actions based on quantitative drought indicators. The methodology is adequately parameterized to allow for the necessary changes that will be introduced during the negotiation stage.

2 Drought Monitoring System

The basis of any drought management plan is a robust system of indicators that can identify and diagnose anomalies in water availability and can provide the basis for early detection of drought episodes (Gustard et al. 2004). A comprehensive study of hydrometeorological time series and drought indices in the basin (Flores-Montoya et al. 2003) led to the definition of a drought indicators system. The system is in continuous revision, taking into consideration the availability of new information and the progress in knowledge of the hydrologic behavior of the basin.

Variables used as early warning levels to predict droughts are grouped in two categories: informative and operational. Informative variables provide information on the development of the drought, and are used as a monitorization tool. Executive variables are objective indicators that are used to trigger specific actions in an operational context (Fisher and Palmer 1997).

Drought is a complex phenomenon, which evolves slowly in time and may affect different regions with varying levels of intensity. No single indicator can encompass the complexity of drought development (Hisdal and Tallaksen 2000). Effectiveness is greatly enhanced if multiple indicators are used to describe drought extension and severity. Values used in the Tagus Basin are: significant departure from normal values in cumulative precipitation or streamflow during the hydrologic year in representative rain and stream gauges, reservoir levels, classical drought indices, like the Standardized Precipitation Index (Guttman 1999) or the Surface Water Supply Index (Garen 1993), abnormal thickness of snow pack during winter months and depletion of piezometric levels in aquifers.

The combination of the above indicators can provide decision makers with enough information to understand the drought phenomenon and estimate its effect. Although these informative indicators are very useful to understand and characterize droughts, management of a multidimensional array of indicators can limit the effectiveness of decision making. There are systems, like the Tiétar basin, where a different set of indicators has to be used in every season. In fall and winter months indicators are based on snowpack and streamflow, because flood control operating rules prevent from storing water in the reservoirs. In spring and summer months, indicators are mostly based on reservoir storage. In order to simplify operation, a normalization of indicators is performed, using a range from 0 to 1. The value 0.5 corresponds to average conditions in the basin, and the value 0 corresponds to the driest conditions in historic record for the indicator. A weighted average of normalized indicators is used in systems with more than one indicator.

In the drought management plan, the monitoring system should be linked to specific actions through a limited set of indicators that can be used as triggers of drought mitigation measures. For this reason, a subset of indicators has been selected as operational variables, which are used as thresholds to trigger specific actions.

The value that best describes water scarcity in regulated systems is the depletion of water stored in important reservoirs below critical levels. Whenever the development of a meteorological drought is being discussed, water managers check for stored water in the reservoirs in order to decide whether there is a significant risk of water deficit. Reservoir storage complies with most of the requirements proposed by (Steinemann et al. 2005) for drought indicators and triggers and is adequate for decision making, because it can be interpreted in terms of risk of failure of the system.

Therefore, the operational set of variables that have been selected to link with actions in the drought plan are the sum of volumes stored in the reservoirs in every system. These values are readily available through the hydrographic service, and are of public domain, so users can have easy access to them.

3 Basin Drought Policy

The Tagus Basin drought policy can be summarized as a list of possible management actions to be taken in case of drought. The catalogue of possible actions is restricted by the legal competences that are attributed to the organism, but the resulting list includes a great number of actions.

These options are very diverse in nature, have different effectiveness and imply multiple economic and social impacts (Wilhite 1997). In every practical case, only a number of measures are feasible and potentially effective at a reasonable cost. The operational effectiveness of the drought management plan is greatly enhanced if the selected measures for every system are grouped in packets, which are applied if certain conditions are met. In the Tagus Basin Plan, drought management strategies are grouped in three scenarios, corresponding to increasing levels of severity: pre-alert, alert, and emergency scenarios.

– Pre-alert scenario. The pre-alert scenario is declared when monitoring shows the initial stage of drought development, which corresponds to moderate risk of consuming all water stored in the system and not being able to meet water demands. The management objective in the pre-alert scenario is to prepare for the possibility of a drought. This means to ensure public acceptance of measures to be taken if drought intensity increases by raising awareness of the possibility of societal impacts due to drought. The kind of measures that are taken in the pre-alert situation are generally of indirect nature, are implemented voluntarily by stakeholders and are usually of low cost. The goal is to prepare the organism and the stakeholders for future actions. Regarding the Basin Authority, main actions are intensification of monitoring, usually through the creation or activation of drought committees, and evaluation of future scenarios, with special attention to worst case scenarios. Regarding the stakeholders, the focus is communication and awareness. Generally, non-structural measures are taken, aimed at reducing water demand with the purpose of avoiding alert or emergency situations.
– Alert scenario. The alert scenario is declared when monitoring shows that drought is occurring and will probably have impacts in the future if measures are not taken immediately. There is a significant probability of having water deficits in the time horizon. The management objective in the alert situation is to overcome the drought avoiding the emergency situation by enacting water conservation policies and mobilizing additional water supplies. These measures should guarantee water supply at least during the time span necessary to activate and implement emergency measures. The kind of measures that are taken in the alarm situation are generally of direct nature, are coercive to stakeholders and are generally of low to medium implementation cost, although they may have significant impacts on stakeholders' economies. Most measures are non-structural, and are directed to specific water use groups. Demand

management measures include partial restrictions for water uses that do not affect drinking water, or water exchange between uses. This may be a potential source of conflict because user rights and priorities under normal conditions are overruled, since water has to be allocated to higher priority uses.

– Emergency scenario. The emergency scenario is declared when drought indicators show that impacts have occurred and supply is not guaranteed if the drought persists. The management objective is to mitigate impacts and minimize damage. The priority is satisfying the minimum requirements for drinking water and crops. Measures adopted in the emergency scenario are of high economic and social cost, and they should be direct and restrictive. Usually there has to be some special legal coverage for exceptional measures, which are approved as general interest actions under drought emergency conditions. The nature of the exceptional measures could be non-structural, such as water restrictions for all users (including urban demand), subsidies and low-interest loans, or structural, like new infrastructure, permission for new groundwater abstraction points and water transfers.

This approach requires the definition of objective criteria to declare each of these scenarios based on quantitative values. Three important parameters are relevant to describe drought scenarios: the time horizon of the analysis, the probability of having water shortages and the expected deficit volume. The time horizon depends on the nature of the regulation of the system. Within-the-year storage systems would only consider the time period till the end of the hydrologic year, while over-the-year storage systems may consider several years. The probability of shortage must reach a balance between the certain damages that will be caused by the implementation of drought measures and the probable future damages that will be avoided by them. Finally, the expected deficit volume will depend on the nature of the demand (urban use, irrigation, hydropower, etc.). These parameter values should be agreed by all stakeholders through a negotiation process that requires the use of water resources simulation models in order to quantify these thresholds, as is discussed in the next section.

4 Definition of Drought Thresholds

The operational implementation of the plan requires a connection between the system of drought indicators and selected measures. To avoid untimely negotiations, the drought plan contemplates the activation of the set of measures associated to a drought scenario 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. Computer modeling is an essential tool to analyze the problem and to find a consensus among users by testing different options.

The objective of the analysis is to define the thresholds for the declaration of the pre-alert, alert and emergency scenarios. Since future reservoir inflows are uncertain, these thresholds should be formulated in probabilistic terms (Steinemann 2003). Most methodologies applied in practice are based on the supply side: they use hydrological indicators, and thresholds are defined by comparing indicator values to some historic reference value. In their analysis, they do not account for the characteristics of the water supply system, the nature or vulnerability of demands, or the social or institutional constraints in water management. Fisher and Palmer (1997) argue for the necessity of a more dynamic indicator relating supply and demand, and present a methodology for a municipal water supply based on the Days of Supply Remaining Index.

In the methodology proposed in this paper, thresholds are defined as the available storage in the system, *S*, that is required to satisfy a fraction, *f*, of the demand in a time horizon, *h*, with a given probability, *p*. Values of *f*, *h* and *p* are model parameters that should be fixed though discussion with stakeholders. They depend on several factors: the type of the demand in the system (urban, irrigation, hydropower, etc.), the reliability of the current water supply system, the alternative management strategies that can be applied during droughts, the vulnerability of the demand to deficits of a certain magnitude, etc.

The Tagus basin is composed of 14 main water resources systems, with important interconnections in most of them. Four systems are used in this paper as an example of the proposed methodology: Cabecera, Madrid, Alberche and Tiétar. Main characteristics of the systems are listed in Table I. ?The Cabecera regulation system consists of two large reservoirs that supply local demand (irrigation, hydropower and environmental flows) and a water transfer to the Segura basin, located in South-east Spain. The regulation cycle in the Cabecera system is hiperannual, with long dry and wet periods. Over-the-year storage is crucial to supply demands in dry periods, which may last one decade or more. The Madrid water supply system consists of 17 reservoirs in the Jarama and Guadarrama basins that supply an urban demand of 500 Mm^3/year, although the system has other alternative sources, such as groundwater or transfer from the Alberche basin. The regulation cycle in Madrid is normally annual, but persistent droughts can affect reservoir levels during two or three consecutive years. Regulation in the Alberche and Tiétar systems is based on an annual cycle. Storage is depleted significantly only in very dry years, and it usually returns to normal levels in the following year. The Tiétar system supplies an irrigation demand, while the Alberche system supplies a mixed local demand of urban use, irrigation, hydropower and environmental flows and an external demand of a maximum of 170 Mm^3/year to Madrid urban supply in drought periods. The Alberche system is a good example of the nature of conflicting interests among stakeholders under drought conditions. If a drought is declared in the Alberche system, decisions have to be made regarding the restriction of water consumption for hydropower production or irrigation in order to protect urban water supplies.

The proposed methodology can be used with any water resources simulation model of the system. In order to present it, a simplified model of each of the water resources systems of the basin was built. Although there are strong interactions between subsystems, considering them independently is a necessary simplification, since management actions are applied in every subsystem depending on local conditions in the subsystem. The simplified model considers only a single reservoir, with storage capacity equal to the sum of all reservoirs in the system. Inputs to the system are the regulated flows, which are flows in the

Table I Main characteristics of four representative systems of the Tagus Basin

System	Mean flow (Mm^3/year)	Coeff. of variation	Min. flow (Mm^3/year)	Storage (Mm^3)	Demand (Mm^3/year)
Cabecera	1,200	0.48	350	2,400	980
Madrid	750	0.42	200	900	500
Alberche	650	0.51	110	250	180
Tiétar	900	0.52	155	115	170

contributing basin to the reservoirs, and non-regulated flows, which enter the system downstream of the reservoirs. The model simulates the operation of the reservoir considering losses to evaporation and restrictions imposed by environmental constraints.

The model was initially used to estimate the volume that is required every month to satisfy 100% of the demand during different time horizons. For every month in the simulation period, an iterative procedure was applied. The model was initialized with full reservoirs. Reservoir volume was decreased until a deficit was reached within the time horizon. The results for four representative systems in the basin (Tiétar, Alberche, Madrid and Cabecera) are shown in Figure 1. These results show the different nature of regulation in the systems, although the hydrologic regime of natural resources is similar in all of them. Droughts in the Tiétar and Alberche systems have impacts during more than one year only occasionally. In the Madrid water supply system the effects are seen during three and even four years. In the Cabecera system the effects of droughts have longer persistence, spanning several years. Variations in demand and reservoir volume compared to natural resources explain these differences.

By analyzing the results produced by the model, graphs like those presented in Figure 2 can be obtained. The graphs show, for every month, the cumulative probability distribution of required storage volumes to supply 100% of the demand during a time horizon of one year. For each month, these graphs have been produced by running the simulation model with all subsets of the historic inflows beginning that month for every level of reservoir storage and identifying the required reservoir storage to supply all the demand without deficit during the time horizon of one year. By sorting the values of reservoir storage, an estimation of the cumulative probability distribution of required reservoir storage is obtained. In a probabilistic sense, these graphs may allow to estimate the probability of satisfying 100% of the demand during one year given the volume stored in the reservoir in a certain month.

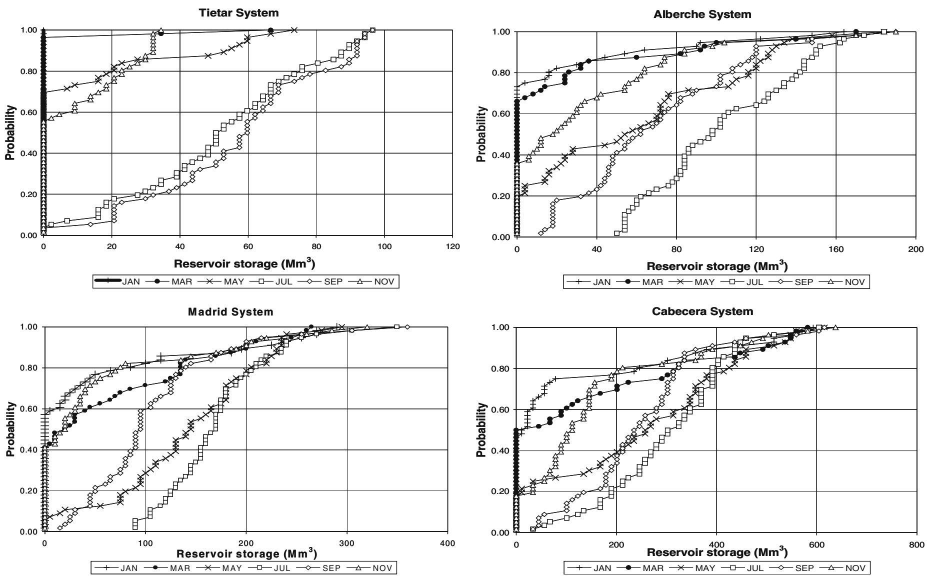

Figure 1 Required storage volumes to supply 100% of the demand for different time horizons compared to simulated storage for four representative systems of the Tagus Basin.

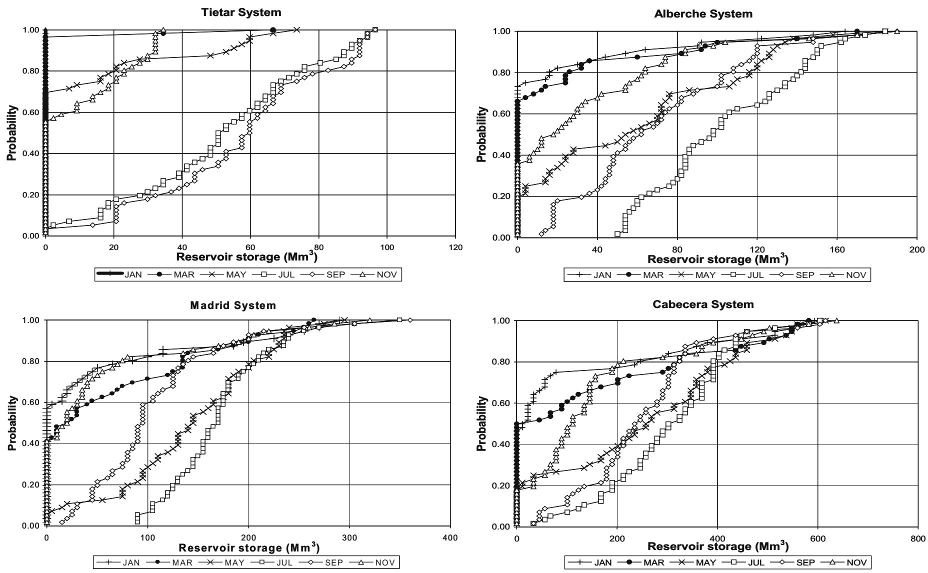

Figure 2 Cumulative probability distribution of required reservoir storage to supply 100% of the demand for one year in four representative systems of the Tagus Basin.

The graphs shown in Figure 2 and similar graphs generated by changing model parameters (the time horizon or the fraction of the demand that is satisfied) are used as a basis to declare pre-alert, alert and emergency scenarios. The definition of parameter values to declare drought scenarios in every system is adopted through discussion with stakeholders. There are two main factors to be considered in this discussion: the vulnerability of demands and the effects of drought declaration.

The characteristics of demands in every system are the first factor to assign values to model parameters. Demands having only one single source of supply are more vulnerable and require stricter parameter values than those having alternative sources. In this group, demands having such sources available exclusively to themselves are less vulnerable than those sharing them with other demands. The Alberche system provides water supply for urban, irrigation, hydropower, and recreational uses, and is the major source of emergency water supply to Madrid. Although local demands in the Alberche system have good reliability, the drought situation in Madrid can affect all uses in the Alberche system significantly.

The expected effects of drought declaration should also be balanced versus drought risk. In systems where demands are close to average natural resources, like, for instance, the urban water supply to Madrid, there is little margin for action, and drought declaration may have very important social and economic impacts. Most emergency measures for Madrid imply having to alter existing water rights, face the development of new transport or storage facilities under great social pressure or impose stronger rules and penalties and stricter control. If the drought situations are declared very frequently, the global effects may be even worse than the no-action approach.

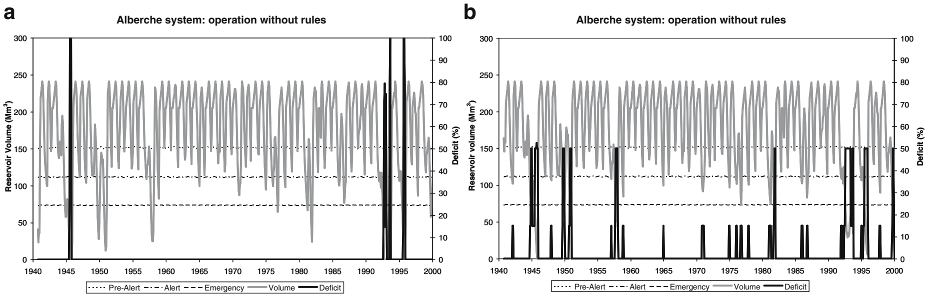

Figure 3 Simulation of the Alberche system **a** without implementing drought management rules; **b** after implementing drought management rules.

5 Model Validation and Discussion

Model validation was performed by simulating the systems with and without the implementation of drought management rules. The results of system simulation without rules are shown in Figure 3a for the Alberche system. There are three severe drought episodes in the historic record in which the reservoirs of the system are completely empty, and there is a deficit of 100% of the demand during several months. This situation is catastrophic, and should be avoided by defining drought management rules that conserve water in the system, at least to satisfy the minimum needed for urban water supply. As a first approximation, these rules have been simulated as reductions of the demand supplied by the system in every drought scenario. These rules are defined as follows:

- The pre-alert scenario is declared when there is a 10% probability of not being able to supply 100% of the demand in one year. In this scenario, no specific demand reductions are imposed. Only awareness measures are contemplated.
- The alert scenario is declared when there is a 30% probability of not being able to supply at least 85% of the demand. In this scenario, a reduction of 15% of the demand is imposed, which corresponds to a reduction of 35% in supply to irrigation and no reduction in supply to urban demand. Irrigation can be supplied using waters from the nearby Tagus river, although farmers do not want this option, due to the lower quality and the cost of pumping.
- The emergency scenario is declared when there is a 50% probability of not being able to supply 50% of the demand. In this scenario, a reduction of 50% of the demand is imposed, which corresponds to no supply to irrigation and 15% reduction in supply to urban demand. Urban demand can use alternative water supplies, like in the case of the cities of Madrid, Talavera and Toledo, but this possibility depends on the situation of their own water supply systems.

Results of this simulation are shown in Figure 3b. The proposed rules can reduce maximum deficit in the system to 50% of total demand, but at the cost of more frequent restrictions. There is always this tradeoff between water conservation measures and drought risk. Early response to drought risk implies producing restrictions that could have been avoided, but it can also avoid important deficits of catastrophic consequences.

6 Conclusion

The methodology that was used to draft the Drought Management Plan in the Tagus Basin has been presented. Drought mitigation is an essential feature of the Tagus Basin. The severity of droughts, in terms of wide spatial coverage and intense water deficits, requires that mitigation measures be discussed and agreed in advance. User participation in the process requires that the methodology be clearly specified and parameterized. The methodology is based on a system of drought indicators and a list of pre-specified drought mitigation actions for every system. In discussions, all users generally agree on the importance of drought indicators and on the rationale of the proposed measures. The disagreements usually concern the timing of measures. Users that are going to be benefited by measures, because their demands will be protected due to the high priority of urban supply, tend to encourage early action, even at the risk of incurring frequently in false alarms and unnecessary restrictions. Other users, whose demands are going to be restricted because of lower priorities of irrigation or power production, tend to support the delay of the application of exceptional measures, even at the price of depleting the reserves completely. The proposed methodology can help in structuring these discussions using a quantitative basis. Operational drought indicators are used to declare drought scenarios, which are associated to the implementation of managing actions. The thresholds for drought scenarios are defined through a model that estimates the probability of having a given deficit in a certain time horizon for each value of the drought indicator. In the discussion of the Drought Management Plan, stakeholders should agree on the values of the parameters (probability, deficit and time horizon) that should be used for each type of demand. The results obtained during the validation phase are encouraging, although there are still certain features that will have to be improved during the process of approval of the plan. Consensus among stakeholders will enhance the effectiveness of the Drought Management Plan because water users will be exposed to the economic significance of management measures and will understand discussions about the application of structural measures as opposed to improvement of management actions in the long term.

References

Fisher S, Palmer RN (1997) Managing water supplies during drought: triggers for operational responses. Water Resources Update 3(108):14–31

Flores-Montoya F, Garrote L, Martin-Carrasco F (2003) The hydrologic regime of the Tagus Basin in the last 60 years. In: Proceedings of the XI World Water Congress. Water Resources Management in the 21st Century, IWRA, Madrid

Garen DC (1993) Revised Surface Water Supply Index (SWSI) for Western United States. J Water Resour Plan Manage 119(4):437–454

Gustard A, Young A, Rees G, Holmes M (2004) Operational hydrology. In: Tallaksen L, van Lanen, HAJ (eds) Hydrological drought. Processes and estimation methods for streamflow and groundwater. Elsevier, Amsterdam, The Netherlands, pp 455–498

Guttman NB (1999) Accepting the standardized precipitation index: a calculation algorithm. J Am Water Resour Assoc 35(2):311–322

Hisdal H, Tallaksen L (2000) Drought event definition. ARIDE Technical Report 6. Department of Geophysics, University of Oslo, Oslo

Steinemann A (2003) Drought indicators and triggers: a stochastic approach to evaluation. J Am Water Resour Assoc 39(5):1217–1233

Steinemann A, Hayes M, Cavalcanti L (2005) Drought indicators and triggers. In: Wilhite D (ed) Drought and water crises. Science, technology and management issues. CRC, Boca Raton, Florida, pp 71–92

Wilhite D (1997) State actions to mitigate drought: lessons learned. J Am Water Resour Assoc 33(5):961–968