18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Decision Support System for Drought Planning and Management in the Jucar River Basin, Spain

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Abstract: Most watersheds in East and South-East Spain can be classified as semi-arid or arid with large space and time variability in precipitation and river flows. Therefore, water resource systems planning and management must be done with emphasis on drought preparation and mitigation. Administration of water is performed at basin scale by Basin Agencies (Confederaciones Hidrograficas) since early in the 20th century, and water laws enforce the design and implementation of Basin Plans (BP), since 1985, and of Special Drought awareness and mitigation Plans (SDP) at basin and local scales, since 2000. The use of models and Decision Support Systems (DSS) has played an important role in the development of the Jucar Basin Plans for almost two decades, as well as for the development and implementation of the Special Drought awareness and mitigation Plans (SDP). The SDP's have been formulated according to a proactive approach to drought preparedness and mitigation. They include long term (planning), medium term (alert) and short term (emergency and mitigation) measures that are activated using Standardized Drought Monitoring Indicators (SDMI) based on the use of combinations of data provided by the ASAS on precipitation, storage in reservoirs, groundwater levels, and flows in rivers. The SDMI and the curves of thresholds for assessment of the drought situation have been calibrated by intensive use of DSS for drought risk estimation. Besides of the regular use of the SDMI, DSS are also permanently used at the real time management board meetings to assess drought risks and vulnerability at medium and short terms. When entering into a drought alert or emergency situation, DSS are a way to evaluate the effectiveness of the measures to modify the risks and to mitigate the impacts of the drought. This is of great help in the negotiations among the parties in the participatory drought committees set up in emergency situations. In this contribution, the experience using these tools during the 2005-2008 drought is reported. This is the most intense hydrological drought registered in the basin in recorded history (since 1940). Due to the highly stressed situation of the basin (ratio of used to renewable resources is around 0.7) situations like this threaten economic uses of water and environment, with big potential damages. Among the measures used during this drought we can find increase of efficiency in water use; improvement in control devises for surface water diversion, groundwater abstraction, and environmental flows; continuous monitoring and inspection of water use and environmental state; anticipated conjunctive use of surface and groundwater, direct reuse of treated wastewater, combined use of two neighbor basins, temporary water rights purchases, and emergency works to improve connectivity in the system. As a result, the worst drought in modern times has been passed with relatively low economic and environmental damages; urban supply was always fulfilled; and conflicts among users solved in an atmosphere of transparency, and cooperation fostered by the mentioned methodologies. DSS for Jucar Basin has been developed using Aquatool DSS Shell developed at Technical University of Valencia (UPV), facilitating the development and use of hydrological, management, water quality and risk assessment models by the Basin Agency professionals.

Keywords: *Decision Support Systems (DSS), Drought Planning and Management, Spain*

1. INTRODUCTION

Most watersheds in East and South-East Spain can be classified as semi-arid or arid with large space and time variability in precipitation and river flows. In addition, water usage is very intense, being very frequent to find ratios of used resources to renewable resources very close to 1, or even greater than one (this can be done, for instance, by water reuse, aquifer overexploitation, and water imports from other basins). Therefore, water resource systems planning and management must be done with emphasis on drought preparation and mitigation. Administration of water is performed at basin scale by Basin Agencies (Confederaciones Hidrograficas) since early in the 20th century, and water laws enforce the design and implementation of Basin Plans (BP), since 1985, and of Special Drought awareness and mitigation Plans (SDP) at basin and local scales, since 2000.

The Jucar Basin Agency (Confederacion Hidrografica del Jucar, CHJ) administers an extension of 42,989 km^2 including several adjacent basins that flow to the Mediterranean Sea in Eastern Spain (Figure 1). As depicted in this paper, the use of models and Decision Support Systems (DSS) has played an important role in the development of the CHJ Basin Plans for almost two decades, as well as for the development and implementation of the SDP's. The SDP's have been formulated according to a proactive approach to drought preparedness and mitigation. They include long term (planning), medium term (alert) and short term (emergency and mitigation) measures that are activated using Standardized Drought Monitoring Indicators (SDMI) based on the use of combinations of data on precipitation, storage in reservoirs, groundwater levels, and flows in rivers. The SDMI's and threshold curves for assessment of the drought situation have been calibrated by intensive use of DSS for drought risk estimation. Besides of the regular use of the SDMI, DSS are also permanently used in real time management at board meetings to assess drought risks and vulnerability at medium and short terms.

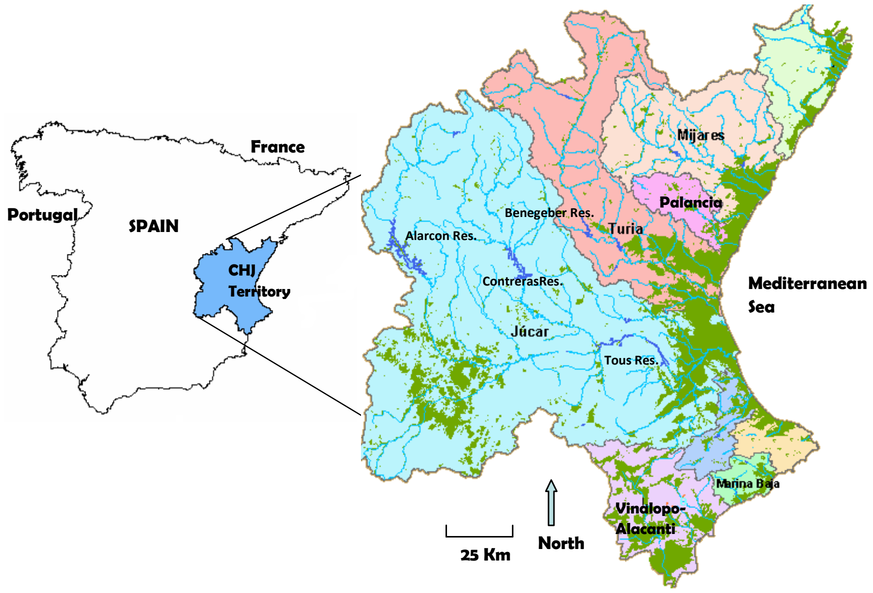

Figure 1. Location of the basins that constitute the CHJ territory.

During the years 2005 to 2008, a severe drought was experienced in CHJ area, mainly centered in the two larger basins, Jucar and Turia. It has been the most intense hydrological drought registered in the basin in the recorded history of hydrological flows (since 1940). In the paper it will be described how the drought was managed, and how the DSS played an important role as tool that provide information for risk estimation, assessment of effectiveness of mitigation measures, and as a common shared vision of the water resources system in the resolution of conflicts among stakeholders.

2. THE JUCAR AND TURIA RIVER BASINS

Among the several basins included in CHJ territory, the larger ones are the Jucar River Basin (22,378 km^2), and the neighboring Turia River Basin (6,913 km^2). In the Valencia coastal plain, where both rivers have their final parts, and between both mouths, there is a shallow lake called Albufera (2,300 ha), with an associated wetland (23,000 ha). Both, the lake and the wetland, depend on return flows from irrigation areas belonging to both basins, and also on groundwater flows from the coastal aquifer beneath the plain. A great deal of information about the CHJ and its basins can be found in CHJ, 2005, and is available at CHJ webpage (www.chj.es). Therefore, only the relevant information needed for understanding the paper will be presented herein.

The main reservoirs for water supply are Alarcón (1100 hm^3), Contreras (400 hm^3) and Tous (400 hm^3), in the Jucar basin, and Benageber (228 hm^3) and Loriguilla (50 hm^3), in the Turia basin. Average annual inflows to reservoirs are 1300 hm^3/year in Jucar Basin, and 285 hm^3/year in Turia Basin. Groundwater plays an important role in both basins. Both have large calcareous aquifers in the northwestern upper parts, where the rivers are born, providing base flows. They also have important aquifers in the middle part, as the Mancha Oriental aquifer, in the Jucar basin, that used to provide important base flow to the river, but nowadays it is being overexploited, which is causing the inversion of flows, so the river looses water to the aquifer in spring and summer. And finally, the coastal alluvial aquifer of Plana de Valencia occupies the coastal plain, where both rivers have their lower parts, in their way towards the Mediterranean Sea.

Water in both basins is used mainly for urban water supply (including industry supply), irrigation, and hydropower generation. The main urban demands are the metropolitan area of Valencia (30 hm^3/year from Turia river, and 90 hm^3/year from Jucar river); the city of Albacete (15 hm^3/year); and the city of Sagunto (8 hm^3/year). Surface water is used in the traditional irrigated areas, mainly in the lower Jucar (50,000 ha), and the lower Turia (30,000 ha), and more recently (20^{th} century) in the middle basin irrigated areas of the Jucar (20,000 ha) and the Turia (20,000 ha). The last ones use frequently groundwater as a supplement of surface water deliveries. Another irrigated area in the middle Jucar basin, reaching to 100,000 ha at present, is using around 400 hm^3/year of groundwater from Mancha Oriental aquifer, and at present can use up to 35 hm^3/year of surface water in order to reduce the aquifer overexploitation.

3. USE OF THE DSS IN PLANNING PHASE

During the design of the Basin Plan for Jucar and Turia basins, there was an intensive use of DSS that were set up using Aquatool, a generalized tool, or DSS Shell (DSSS) produced by IIAMA-UPV to develop DSS's for integrated water resources planning and management. It includes, among other, modules for basin management simulation, basin management optimization, aquifer flow modeling module, drought risk assessment, economic assessment, water quality simulation, and ecological flows analysis. It has friendly graphical design and database management capabilities, and provides control on the execution of the models and on the analysis and reporting of results. The DSSS allows the user to input and modify, in a geo-referenced graphical way, the configuration of a water resources system, and facilitates the input and management of graphically geo-referenced data bases containing the physical characteristics of the components of the schemes and knowledge bases containing data related to decision variables and management parameters, in order to replicate the judgment of experts in the basin management teams (i.e., operating rules). In Figure 2, the schematics of the Turia and Jucar Basins in the DSS's can be seen.

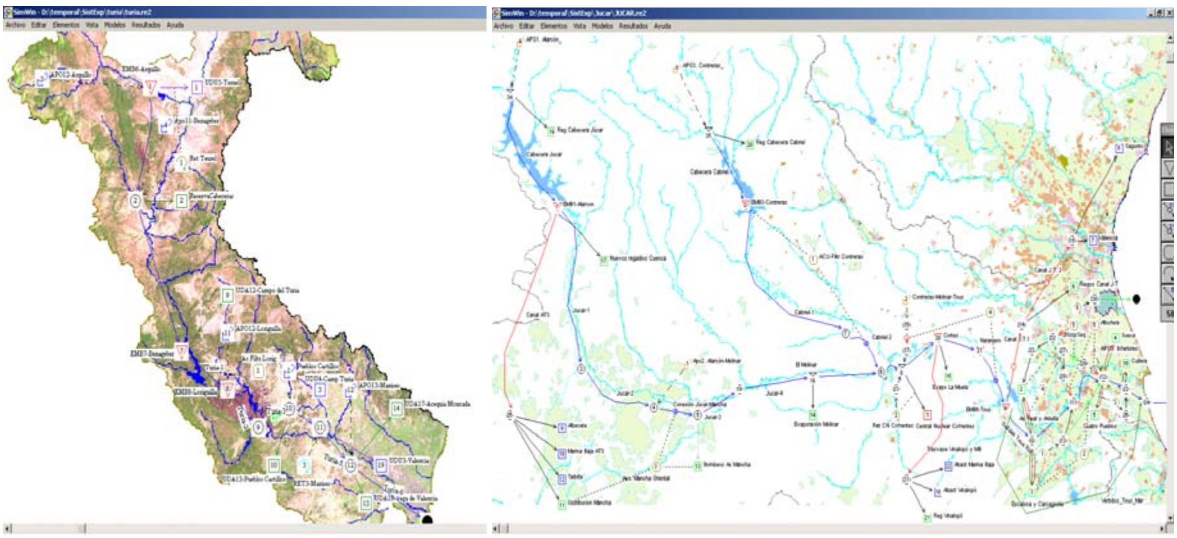

Figure 2. Schemes of the Turia (left) and Jucar (right) river basins used in the DSS.

Once the system is completely defined, the user can perform simulation runs of the management for multiple different alternatives, time horizons and scenarios, using different hydrological data and also different operating policies. Results include flows and state of the elements, and multi-objective performance indicators (reliability, resiliency and vulnerability of demands and environmental requirements). Therefore, the model is useful for the evaluation of alternatives, to analyze planning decisions and to assess tradeoffs between alternatives. Risks associated to planning decisions can also be assessed since, besides of deterministic analysis, implicit stochastic analysis can be performed. For this purpose, multiple future hydrological scenarios are generated, and probabilities for the variables of interest, as well as probability distribution functions, are obtained from multiple simulations. In the same fashion, risk associated with real time management of the system can be assessed. In this case, the module for generating future scenarios produces hydrologic scenarios conditioned to the hydrologic state of the system at the moment of the consultation (i.e., conditioned to recent flows and aquifers state). The results of the analysis can be obtained in the form of written reports (either detailed for the entire time horizon or summarized as mean values and performance indicators), time series and average graphics, and probability distribution along the time horizon (i.e., percentiles graphics), or exceedance probabilities for a given variable at a given time. A more detailed description of the DSS tool, as well as of practical applications for integrated planning and management in other Spanish basins can be found in Andreu et al. (1996),

4. USE OF THE DSS IN DROUGHT PLANNING, MONITORING, AND RISK ESTIMATION.

Since the year 2000, Spanish water law requires the basin agencies to develop Special Drought Plans (SDP) in order to turn the traditional reactive crisis management approach into a proactive approach. The SDP for CHJ territory (CHJ, 2007) includes monitoring for early drought detection, drought stages definition, and the measures to be applied in each of the stages. CHJ has developed operative drought indicators (CHJ-ODI), which are fully described in the SDP, and also in Estrela et al., 2006. In essence, the CHJ-ODI, use the real time information provided by the Automatic Data Acquisition System of CHJ on the state of reservoirs, aquifers, flows in rivers, and precipitation, to produce standardized indexes for some selected elements in the basin, and combine them into a single standardized index for each basin. The usefulness of the CHJ-ODI comes from its relationship with the results of the simulation of the management with the DSS. The water resources system management is simulated for a large historical hydrological scenario, with current facilities and demand scenarios, and the different situations of water supply (i.e.: normality, pre-alert, alert and emergency) are correlated with the values of the CHJ-ODI, obtaining a calibration of the indexes that renders them useful for early warning, risk perception, and for starting different types of preparation and mitigation measures according with the situation. Nowadays, drought monitoring is performed on a monthly regular basis, and the reports are displayed in the CHJ web page (www.chj.es).

CHJ-ODI have shown to be useful indicators for early warning, and for risk perception by the public. But, in order to manage droughts, more elaborated and detailed information is needed to better assess the risk and the effectiveness of the measures that are candidates to modify the risks and to mitigate the effects of the drought on the established uses and on the environment. This is why, besides the use of the CHJ-ODI to monitor the operative drought, CHJ has gone one step further integrating the long term (planning) and the short term (management and operation), providing coherency between those two time scales, and demonstrating that DSS can be very useful for the real time management of basins, and during drought episodes and their associated conflict situations. As mentioned above, the Aquatool DSSS allows the development and use of real time management models able, for instance, to assess the risk of drought, and the efficacy of proactive and reactive measures (Capilla et al., 1998), and it is being applied on regular basis for the management of the Jucar and Turia basins.

In order to decide real time water allocation, there is a Water Allocation Committee (WAC) in each basin that meets every month, and according with the situation of the system, decides how much water will be delivered, and how much will stay in reservoirs and aquifers. These are participatory committees in which stakeholders are represented, and information for the decision is provided by technicians of CHJ, including the results of the risk assessment models. Following the methodology of drought risk and assessment depicted in Andreu et al. (2006), the probability distribution for all variables of interest (e.g., deficits in water demands, volumes in reservoir storage, deficits in ecological flows, etc.) for every month of the anticipation horizon time (e.g., 12, 24, or 36 months) are obtained. The DSS can show these results in tabular or graphical form showing the evolution of probabilities and percentiles for the water demands and for reservoir storage. Cumulative distribution functions of any state or quality variable at any time can be obtained. Then, the WAC analyzes the results and evaluates the situation. If the estimated risks are acceptably low, then there is no need to undertake measures. However, if the estimated risks are seen as unacceptably high, then some measures must be applied. In that case, alternatives with sets of measures are formulated, and the modification of risks and the efficiency of measures is assessed. This iterative procedure can be continued until, eventually, an acceptable value of risk is reached and the process ends. The approach can be applied directly to any complex system thanks to the models and data management modules included in Aquatool. Without the development of the DSSs, it would be very difficult, if not impossible; to estimate risks with such a complete vision of the consequences of decisions (either concerning management or infrastructure).

5. THE 2005-2008 DROUGHT MANAGEMENT EXPERIENCE.

In the year 2004/05, a severe drought started. In fact, it has been one of the more intense hydrological drought registered in the basin in the recorded history (since 1940). Hydrologic year 2004/05 was ranked the third year with lower total inflows to the ensemble of Alarcon, Contreras, and Tous reservoirs, and 2005/06 was the worst in history.

As it can be seen in Figure 3, in February 2005, stochastic analysis gave an early warning since the probabilities of ending the hydrological year with low storage (between 195 and 390 hm^3 in total) were significant (more than 50%). So, water savings in agricultural uses was encouraged, old "drought wells" in the Plana de Valencia Coastal aquifer were recovered, and new drought wells were projected and drilled. Besides of lowering the application rates, surface water was also saved by conjunctive use with groundwater, so the middle basin irrigation area served by the Jucar-Turia canal increased their groundwater abstraction, and reduced in 30% their surface water consumption. Moreover, the operating rules devised for the system state that, when the total storage in the ensemble of the three reservoirs fall under an established rule curve, it is required to start with conjunctive use practices in the lower basin. So, in August 2005, the traditional irrigated areas of the lower basin started to use the drought wells in order to reduce their surface water consumption. It is interesting to notice that energy consumption in these wells is not paid by the traditional users, but by the junior rights users and by the urban users.

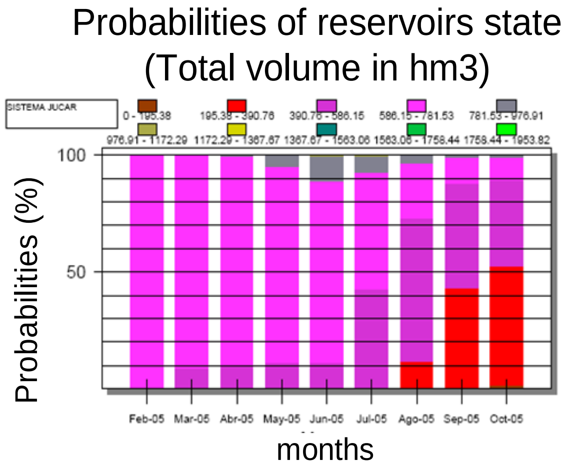

Figure 3. February 2005 assessment of storage probabilities for 2005 campaign.

After the end of the 2004/05 hydrological year, the situation did not improve, and a so called "Permanent Drought Committee" (PDC), with special powers to administer the basins of CHJ under emergency situations was set up. The PDC was composed of representatives of CHJ; of regional governments (Castilla la Mancha, Valencia, and Catalonia regions); of agricultural, industrial, and urban uses; of the Ministry of Agriculture; of the Spanish Geological Institute; of nongovernmental environmental organizations; and of labor unions. As it can be seen, it was a participatory committee, in which most stakeholders were represented, and its missions were: to take decisions on water management during the drought in order to get equilibrium between the interests of different sectors, different groups of users in the same sector, and environmental needs, and to mitigate the impacts of the drought; to perform a continuous monitoring in order to control the achievement of the decisions, and to follow the evolution of the drought, and its impacts on users, on water quality, and on environment (water quality in the lower Jucar River and in the Albufera wetland were critical issues, as well as low flows in the middle Jucar River and low inflows to the Albufera wetland); and to authorize emergency works in order to improve control and efficiency of water use, connectivity, additional sources development (e.g., drought wells, direct treated wastewater reuse, etc.), in order to improve the reliability of the supply.

In March 2006 the CHJ-ODI gave the image shown in Figure 4 (left), with the maximum emergency situation in the Jucar Basin, and the deterministic and stochastic forecasts for the evolution of reservoir storage obtained with the DSS were as depicted in Figure 5. As it can be seen, the forecast was that if no additional measures with respect to the ones taken in the previous year were undertaken, reservoir storage would reach values bellow 55 hm^3 (minimum environmentally and technically admissible value). So, surface water allocated to irrigation was reduced to 50% of normal supply in traditional users, and to 30% of normal supply to junior water rights. Supplementary supplies from groundwater of about 40 hm^3 were mobilized, as well as 60 hm^3 from recirculation of water in the rice fields in the wetland area.

Other measures included doubling the amount of water supplied to the Metropolitan Area of Valencia coming from the Turia basin, from 30 to 60 hm^3/year, hence reducing the supply from the Jucar River. In order to achieve this without harming much the reserves in the Turia basin, about 60 hm^3 of treated waste water was directly supplied to traditional agricultural users in the lower Turia basin in substitution of surface water. Besides, CHJ purchased temporarily 50 hm^3 of water rights from agricultural users of the Mancha Oriental aquifer, to avoid extracting this groundwater, in order to improve environmental flows in the middle Jucar River. In Figure 5 the deterministic and stochastic forecasts for the evolution of reservoir storage performed calculated in April 06 in the assumption of the application of these measures are shown.

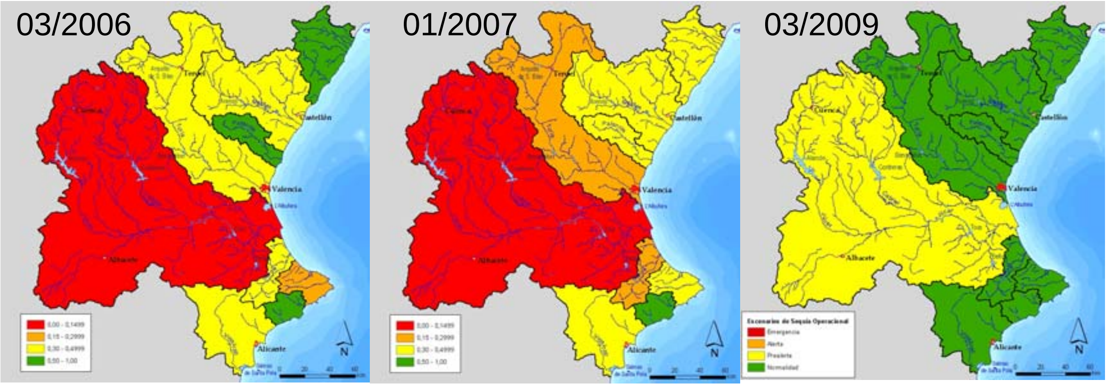

Figure 4. CHJ-Operative Drought Indicators for CHJ basins in March 2006 (left), January 2007 (center), and March 2009 (right).

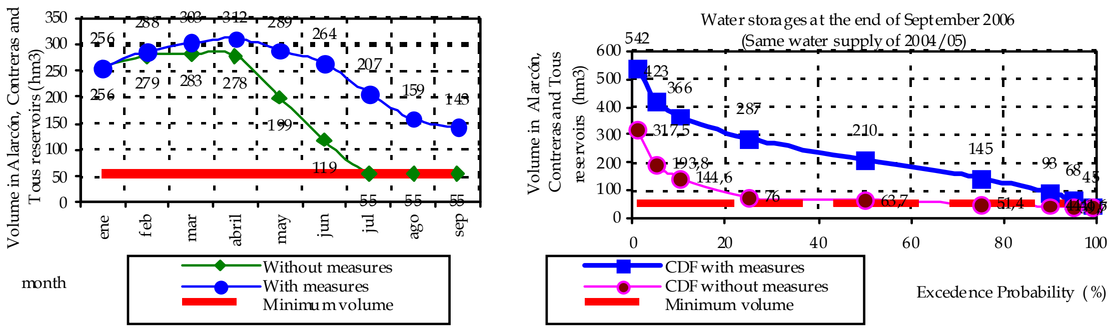

Figure 5. Deterministic (left) and probabilistic (right) forecasts for the reservoir storage evolution in 2005.

It can be seen that final storage was very much improved, and therefore the plan including the measures was approved and implemented. Additional measures included increase of efficiency in water use (a main pipeline and primary distribution network was setup to supply traditional farmers in the lower Jucar in substitution of the old main canal and ditches); improvement in control devises for surface water diversion, further enlargement of the drought wells system, anticipated conjunctive use of surface and groundwater, and increasing of direct reuse of treated wastewater). Also included in the measures adopted, were special monitoring programs for the environmental situation of the basin in critical spots, as the middle reach of Jucar river, where groundwater abstraction can cause river depletion; the lower reach of the Jucar river, where low flows and high pollution loads can cause severe problems; and the Albufera lagoon, which depends on irrigation returns for its inflows. Water quality improvement measures (e.g., removal of algae, and artificial aeration) were applied in the lower Jucar River. Besides, a special groundwater monitoring program was also included among the measures, controlling volume of water abstraction, water levels, and the quality of the water.

In hydrological year 2006/07 and 2007/2008, total hydrological inflows were higher than in the year 2005/06 in the Jucar River, but still under the average, and their distribution was irregular, so the reservoirs in the upper part of the basin received less water, aggravating the low flow problem in the middle Jucar River, so the plans for 2007 and 2008 campaigns approved by PDC adopted very similar measures as the ones included in 2006 campaign, but with increased figures in some aspects in order to achieve the same degrees of drought mitigation and environmental protection as in 2006/07. In the Turia basin, the situation passed from pre-alert in March 2006, to alert in January 2007, due to low hydrological inflows, as can be seen in Figure 4. In 30th September 2008, as a consequence of the continued measures, and of a slightly better hydrology, the reservoir storage in Jucar Basin was 260 hm^3, the best end of a campaign since 2004, and in the hydrological year 2008/09 abundant rainfall is bringing the basins back to normality, as it can be seen in Figure 4 for CHJ-ODI for March 2009. Normality will be attained surely in Jucar basin by June 2009.

6. CONCLUSIONS

Generalized tools to build DSS, or DSS Shells (DSSS), bring the possibility of relatively easy, systematic and homogeneous application of DSS over wide regions, and also provide guidance in the development of the

DSS. An example of the practical use of one of such DSSS (Aquatool), has been presented in this paper and used in practice for many years.

In Integrated River Basin Management, the integration of long term (planning) and short term (management and operation) is very important to provide coherency between those two time scales. DSS can be very useful for the real time management of basins, for instance, during drought episodes and their associated conflict situations. Aquatool DSSS allows the development and use of real time management models able, for instance, to assess the risk of drought, and the efficacy of proactive and reactive measures, being applied on regular basis for the management of basins in the Jucar basin, in Spain.

As a result, the worst drought in modern times in the Jucar basin, lasting from year 2005 to 2008, has been passed with relatively low economic and environmental damages; urban supply was always fulfilled; and conflicts among users solved in an atmosphere of transparency, and cooperation fostered by participatory approaches, and also by the methodologies presented, which relied very much on the results of DSS, and their role as tools for the assessment of risk and of the efficiency of mitigation measures.

Some of the measures were experienced for the first time in Jucar basin, as for instance: water rights purchases; voluntary cuttings in groundwater extraction from Mancha Oriental Aquifer; direct treated wastewater reuse by traditional irrigation in lower Turia basin; conjunctive use of surface and groundwater by traditional irrigation in the lower Jucar Basin, with energy expenses been paid by users with junior rights; and improved control measures for control of water use and environmental flows. And they proved to be very effective in the mitigation of the drought impacts. Therefore, many of these measures adopted in the campaign plans approved by the Permanent Drought Committee will become permanent practices, after a convenient remodeling to adapt for ordinary management, and the lessons learned from this experience will help in the production of new versions of the Basin Plan, and of the Special Drought Plan of Jucar basin.

ACKNOWLEDGEMENTS

The authors would like to thank to the European Communities for financing the project "SEDEMED - Sécheresse et Desertification dans les bassins méditerranées II", ref. 2003-03-4.4-I-010 (INTERREG III B-Mediterranée Occidentale); to Ministerio de Educación y Cultura of Spain (Comisión Interministerial de Ciencia y Tecnología, CICYT) for financing of the project "Sistema de apoyo a la decision de planificacion de cuencas hidrográficas para la adaptación a la directiva marco comunitaria en materia de aguas ", contract CGL2005-07229; and to Generalitat Valenciana for financing the project " Desarrollo de herramientas para gestión de datos sobre Sistemas de Recursos Hídricos mediante entorno de Sistemas de Información Geográfica ", contract GV07/199. As well, gratitude is expressed to Confederación Hidrográfica del Júcar (Spanish Ministry of Environment) for using Aquatool, and for allowing the publication of the case of study presented.

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