METHODOLOGY AND TOOLS FOR INTEGRATED ASSESSMENT OF RESOURCE AND ENVIRONMENTAL REQUIREMENTS COSTS

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Abstract

A methodology for systematic assessment of the resource costs in a water resources system is presented. It is based on the development of integrated hydro-economic simulation and optimization models at the river basin scale. These models can be also used for some other aspects of the economic analysis required by the WFD, as assessment of the opportunity cost of some environmental measures, such as minimum flows in rivers or minimum volumes in reservoirs. The use of hydro-economic simulation and optimization models allows to obtain two complementary measures of these opportunity costs. These models can be developed "ad-hoc" for a specific system, or we can resort to the use of generic tools integrated in Decision Support Systems. New modules have been integrated in the DSS AQUATOOL, incorporating tools to apply the proposed methodology. These tools are been applied to the Jucar Pilot River Basin (Eastern Spain).

I. Resource cost and MROC

According to Article 9 in the WFD, "members shall take account of the principle of recovery of the costs of water services, *including environmental and resource costs*, having regard to the economic analysis conducted according to Annex III, and in accordance with the polluter pays principle".

The cost of water has two broad components: the cost of its provision and its opportunity cost. The concept of resource cost is usually related to the opportunity cost or the cost of forgone opportunities that other alternative users suffer when a scarce resource is allocated to an activity (use). There always be opportunity cost if there is water scarcity, either in a quantity or quality sense, at a specific point in time and space (Brouwer, 2004).

From the point of view of management of water as an economic resource, the key challenge is to ensure that this cost is taken into account in the resource allocation decisions. By ignoring the resource cost, water is undervalued, which can lead to significant errors in investments and water allocation among users (Griffin, 1998; Rogers et al., 1998). Theoretically, if water tariffs include this cost an optimal resource allocation would be reached at the long-run. In this optimal scenario the marginal productivity of water would equal among the different uses and society's welfare would be maximized. Despite the apparent simplicity of the concept, measuring the opportunity cost of water is a difficult task. In the absence of well-functioning water markets, opportunity cost assessment requires "a systems approach and a number of more or less heroic assumptions about real impacts and responses to these" (Briscoe, 1996). This assessment has to be based on a proper system to determine the value of water for the different users in the system.

The marginal resource opportunity cost (MROC) at a specific location and time can be defined as the cost for the system of having available one unit less of resource at that location and time. This value is an indicator of the aggregated "economic impact" of water scarcity and helps to understand how much the users would be willing to pay to mitigate that scarcity. The MROC varies dynamically in time and space, as resource availability and demand's requirements and willingness to pay (WTP) vary. This spatial and temporal variability can only be captured by means of a hydro-economic model of the system that integrates demand, resource and infrastructure under realistic operating rules. Practical values of the resource cost as required by the WFD should be obtained from the analysis of these MROC.

II. Marginal cost of environmental requirements (MOCER)

Minimum ecological streamflow or minimum reservoirs' storage requirements are among the measures to achieve the good ecological status of water bodies. These requirements imply an opportunity cost for the system. Like in the MROC, the marginal opportunity cost of environmental requirements (MOCER) can be assessed as the cost for the system of increasing the environmental constraint in one unit.

Given the difficulty in assessing the environmental costs of water services as environmental damages, in some cases an indirect assessment of components of the environmental cost (art. 9) of certain water services can be provided by the opportunity cost of the measures to maintain the good ecological status required by the Water Framework Directive. Therefore, for the purpose of the cost recovery analysis, the cost of the measures prevent, avoid, or mitigate environmental damages can be can be used as a proxy for the external environmental cost, which should be internalized somehow in order to reach the desired target situation (Brouwer et al., 2004; Maestu et al., 2004). The cost of the measures already in place represents the environmental damage cost already internalized.

This definition can be applied to the valuation of the environmental cost that storage and abstraction services (see list of water services in WFD, art. 2) produce by altering the downstream streamflow regime. On the other hand, the environmental operating constraints are measures to increase the ecologic quality of the river, either physic-chemical quality (increase in dilution by increase in streamflow) and/or biological quality, and thus they are part of the measures whose potential cost has to be evaluated to identify the most cost-efficient combination of alternatives (art. 11, Annex III). The MOCER could be also applied to support Art. 4 derogations with economic arguments.

III. Methodology

The use of hydro-economic models is indispensable to analyze a river basin in an integrated way, preserving the interconnection among its different elements (resources, uses/services, infrastructure), and to discriminate the results for different locations. The models must be capable of properly reproducing surface and groundwater interactions, and must incorporate the value of water for the different uses, as well as the system's operating variable costs. The results of these models capture and highlight the spatial and temporal variability of supply and demands, taking into account resource availability, storage capacity, losses, return flows, and WTP (or marginal economic value) at each water use, as well as the operation of the infrastructure. This representation allows the dynamic assessment of the MROC and MOCER at different locations in the basin.

The methodology proposed aims to quantify the MROC and MOCER in a water resource system by the development and uses of simulation and optimization models whose main characteristics are:

- *Integrated economic analysis at the basin scale.* The river basin is generally the base scale to assess environmental and resource costs, as well as to carry out the cost-effectiveness analysis of the measures to achieve the good ecological status, since it represents the level in which environmental externalities are produced (European Commission, 2000).
- *Conjunctive modelling of surface and groundwater*. In systems in which the groundwater component is important, the model should be able to simulate both surface and groundwater systems, as well as their interaction. Otherwise, significant externalities would be ignored. For example, isolated analysis of an aquifer does not allow the assessment of pumping stresses influence on the ecological status on downstream locations.
- *Incorporation of water economic value functions for water uses and variable operating costs.* The demands are represented by monthly economic value functions that express the relation between the supplied water and the marginal value for each month of the year. The integration of the demand economic function up to a certain level of supply (area under the demand curve) provides the economic benefit imputed to this supply level. The accuracy of these demand curves, assumed as exogenous information for these models, is of paramount importance in the reliability of the model's results. The variable operating costs considered include variable costs of withdrawal, distribution and treatment for both surface and groundwater supply. Fixed costs are considered sunk.
- *Representation of the spatial-temporal variability of water availability.* For this purpose, either long hydrologic time series, representing a wide range of hydrologic events, or synthetic series stochastically generated are employed. Monthly scale is the proper time scale to be able to take into account the periodicity of the hydrologic time series and the seasonal behavior of the demands.

Two complementary approaches are followed. If we define the objective function as the aggregated net economic benefit from water allocation in the system, the **optimization approach** obtains the MROC and MOCER by means of the shadow prices or dual values of the optimization. These results correspond to the economically optimal water allocation, which could be theoretically obtained in an ideal situation of perfect water market. On the other hand, the **simulation approach** assumes that the system is managed following a set of operating rules and institutional constraints. These rules can correspond to the priorities and historical rights, reproducing the current modus operandi of the system. Comparison of the optimizer and the economic simulator results offers conclusions on the resource cost and other economic assessments. The gap between the economic value of the economically optimal water use and the current water allocation system allows assessing the "distance" between the optimum and any management analyzed. The results of the optimization model can provide insight on possible operating rules or strategies to improve the economics results in the system, whereas the benefits of any modification in the management criteria, as modifications for achieving the quality standards required by the WFD, can be assessed by the simulator.

IV. Optimization approach

The hydro-economic optimization model at the basin scale allows to estimate the time series of MROC at various locations in the system, users' WTP of the users, marginal cost of environmental constraints, and economic losses caused by reduction of supply to the demands, among other economic results (Pulido, 2003; Pulido et al., 2004).

In an optimization model, the optimal values of the variables of the dual problem (shadow prices or Lagrange multipliers) provide directly the change in the optimal value of the objective function as a consequence of a marginal unit change in the constraint that corresponds to each dual variable. If the objective function represent the economic result derived from water use in the system, the shadow prices of the balance constraints in nodes of the network flow of the system (including reservoirs and aquifers) provide the net benefit derived of a unit increase of the resource in that node and instant, and so, the marginal resource opportunity cost (MROC). Thus, the optimization model provides time series of the MROC at certain locations of the system.

The shadow price time series associated to a minimum flow environmental constraint provides information on the marginal value for the system on relaxing the constraint in one unit or, by the same token, the benefits forgone to maintain one more unit of minimum streamflow. The results for various levels of constraints show the economic impact on the system as a function of the constraint level applied. Additionally, the optimization model also allows detecting in which cases the physical limitations of the infrastructure or the management rules of the system act as constraint for a more economically efficient resource allocation, depending on the shadow prices associated to the capacity constraints (Pulido et al., 2004).

IV. A. Mathematical model configuration

The objective function to be minimized represents the total cost for the optimization period, including economic losses derived from water shortage in the supply to the consumptive demands, adding pumping and other variable operating costs (Pulido et al., 2004). Deliveries less than the maximum demanded by the users produce economic losses equivalent to the economic value of the water forgone. Economic loss functions for agricultural and urban uses are derived from monthly economic demand functions that express the relation between the quantity of water delivered and its marginal value, ceteris paribus. The area under the demand curve indicates users' willingness-to-pay for water delivered. Economic losses are found by integrating the demand curves from the maximum demand leftward to the delivery. For agricultural demands, these equations must be generally defined for each month within the year, given the variability of the irrigation schedule along the year, whereas for urban demands it can be reasonable to consider seasonal curves with different elasticities, reproducing the seasonal behavior of urban demands (Jenkins et al., 2003). A singular point in the curve is the maximum or target demand. The maximum demand for irrigation corresponds with the delivery that users would demand if water would be available at zero marginal cost. For the urban demands, it can be defined as the product of projected population and per capita water use, including water conservation measures if necessary (Jenkins et al., 2003).

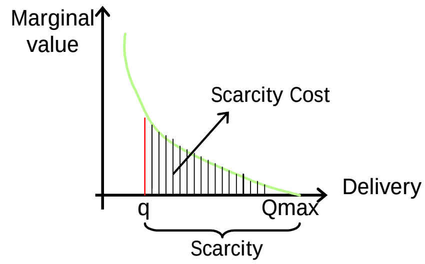

Fig. 1. Scarcity and scarcity cost

The constraints of the model can be classified into:

- *Mass balance equations* for flow at each node in the network. The nodes can have non storage capacity, as those representing river confluences, diversions or intake points, for which the sum of all flow in must equal the sum of all flow out. There are also nodes with storage capacity, comprising lakes and reservoir, in which the mass balance equation includes a term of storage.
- *Upper bound constraints* in flows in conveyance facilities or storage capacity of aquifers or reservoirs, imposed by either physical or management reasons.
- *Physical process equations.* We have to include equations for seepage and evaporation losses in reservoirs and conveyance facilities, and return flows in the demands. For modeling the groundwater subsystems, state and control equations should be included.
- *Lower bound constraints.* Lower bounds may include minimum streamflow in certain river courses, minimum water diverted or delivered, or minimum storage in reservoirs, because of operative, environmental or recreational reasons.
- *Sign constraints* of the variables.

A variety of results can be provided by the model. Direct results include monthly flow and storage time series in the elements of the system's network, marginal economic value of water in each element, and shadow prices corresponding to upper or lower bounds in the different links. These results lead to conclusions on water allocation and operating decisions, as well as estimates of the economic values of changes in the management and/or the capacity of the infrastructure, user's willingness-to-pay for water, and other economic and performance indicators.

IV. B. Case study: the Adra-Campo de Dalías system

The methodology described has been applied to a case study inspired in the system of Adra River basin (Almeria province). In the nearby coastal plain, Campo de Dalias, the high value of the crops produced under greenhouses has led to a spectacular increase of cultivated land, population and water demand (mostly supplied by groundwater from the Campo de Dalias aquifers), generating sea-water intrusion problems. During the period 1987/88 this system begins to receive water imported from the Beninar reservoir, located in the contiguous Adra River basin, by means of the Beninar-Aguadulce channel, to reduce the overexploitation of the aquifers in the Campo. In a previous study of surface and groundwater conjunctive use in the Adra-Campo de Dalias system, different management alternatives were simulated with a simulation model developed by SIMGES, the simulation module of AQUATOOL (Pulido-Velázquez et al., 2002).

A hydrologic-economic optimization model of the Adra's water resource system downstream the Beninar reservoir has been developed. The network flow (Fig. 1) consists of a reservoir and two aquifers that supply water to two agricultural and one urban demand. *Irrigation1* demand, which correspond to the portion of the Campo de Dalías demand that is supplied by the water transfer, receives water from the reservoir through the Canal1 (*Canal Benínar-Aguadulce*). Downstream the reservoir, the traditional irrigation districts of the Adra basin, aggregated as *Irrigation2*, are supplied through streamflow diversions by canals (*Canal2*) and groundwater pumping in the detritic aquifer of the delta (*Delta aquifer*). The water demand for urban supply, *City*, is conjunctively supplied by groundwater pumping in the Delta and streamflow diversions through a pipeline (*Pipeline*). *Beninar reservoir*, in the middle basin of the Adra River, is the main element of storage and flow regulation for water supply (23 Hm^3). Significant water losses by seepage occur in the reservoir, part of which is collected by the carbonate *aquifer of Turon,* which discharges into the river at the *Fuentes de Marbella springs*. The aquifer's recharge comes from the reservoir seepage losses, infiltration in the first reach of the river, and rainfall percolation. The recharge stresses on the Delta aquifer include: rainfall and runoff infiltration, seepage losses in the irrigation ditches, seepage in the last reach of the river, and irrigation and urban return flows. Groundwater outflows include pumping to supply *City* and *Irrigation2* demands and sea-aquifer water exchange. The *Turon aquifer* simulation model has been integrated in the global model by an Embedded Multicellular Model (EMM) of two cells (Sahuquillo, 1986). Since there is no need of a detailed knowledge of the spatial and temporal evolution of the aquifer, this approach provides a simple and mathematically sounded way to model the relationship between recharge and discharge in karstic aquifers. Moreover, the general structure of the solution provided by the EMM can be used to estimate the aquifer's parameters by simple calibration directly from the input and output data of the system. Thus, the limited knowledge of the formation is properly accounted for avoiding the unnecessary construction of a large distributed model where a great number of parameters would have to be estimated. The *Delta aquifer* model is represented using the Eigenvalue Method, which allows efficient integration of distributed parameter models within conjunctive use management models (Andreu and Sahuquillo, 1987).

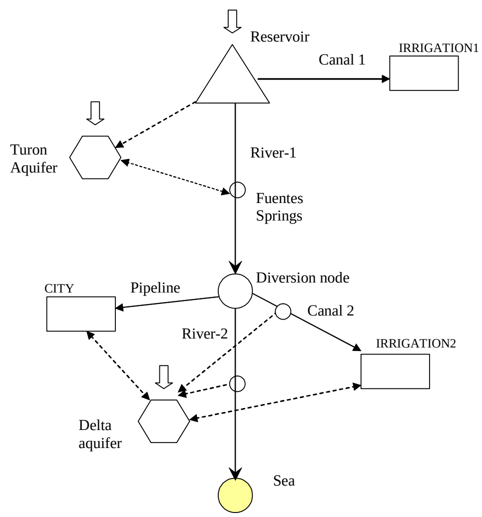

Fig. 1. Conceptual schematic of the Adra's system

The model, programmed in GAMS (Brooke et al., 1998), optimizes the net economic benefit from water management in the system during a ten-year long period with monthly detail. The inflows to the systems (reservoir inflows and rainfall infiltration in the two modeled aquifers) are reproduced through the historical series corresponding to the period from 1945/46 to 1954/55. The *objective function* to be minimized represents the total cost in the system, summation of scarcity costs and variable operating costs. The pumping cost in the Delta aquifer is calculated dynamically as a function of the pumping lift (with an analytical correction to consider well drawdowns) and the pumping rate. Monthly irrigation demand curves are derived from quadratic annual demand curves, which are disaggregated according to irrigation schedules. Considering the lack of data, the urban demand has been characterized by a constant elasticity curve, calibrated from an observed relation quantity-average price and an estimation of the price elasticity of the curve. Given the high seasonality in the residential demand, we have considered four seasonal elasticities, disaggregating the annual demand according to the monthly pattern of water use. The demand economic curves are transformed into penalty functions, which relate water supply and scarcity cost, by integrating the curve function between the water delivered and the maximum level of supply (area under the demand curve).

Fig. 2 shows the temporal variation of MROC at two locations in the system: the reservoir and the node, just before the diversion for the supply of *City* and *Irrigation2*. The time series in the reservoir present two valleys, which correspond to periods in which the shortage is cero and the reservoir is full, so that that unit can not be transferred to a later period. The two peaks of the series correspond to the periods in which the reservoir empty. Even when scarcity (and thus WTP) becomes zero in a month, resource value in the reservoir can remain non-zero, due to the opportunity cost for its later use. The shape of the time series is mimetic to the envelope of the WTP curve for *Irrigation1*. In the series of resource marginal value in the *node*, two circumstances coincide in the valley tracks: the flow rates in the last river reach are greater than the minimum required, and the scarcity is zero for *Irrigation2*.

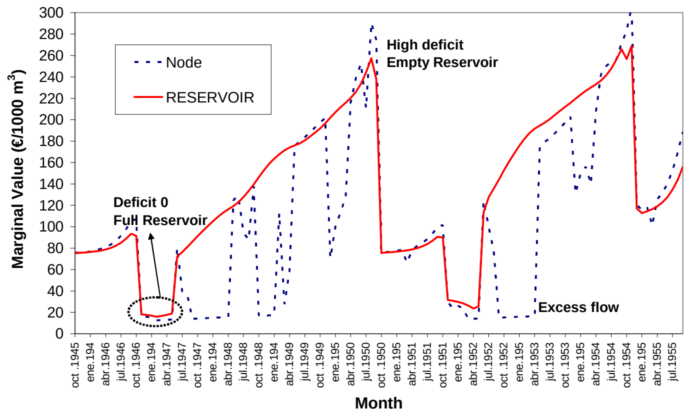

Fig. 2. MROC at node and reservoir

The marginal costs of maintaining the monthly minimum streamflow requirements downstream the diversion node (Fig. 3) are given by the corresponding shadow price series. The marginal value becomes zero in periods in which streamflow exceed the minimum required, in which demands' scarcity is also zero. Except for these months, the environmental cost time series is mimetic with the marginal value series in the node.

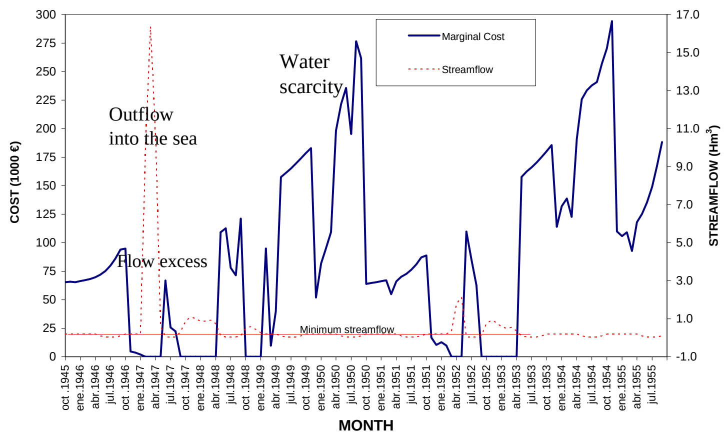

Fig. 3. MOCER at the last reach of the Adra river

V. Simulation approach

In the simulation approach, water is allocated in accordance with a set of operating rules, which can defined with the aim to reproduce the current legal and institutional framework. Unlike the optimization approach, in this case the economic indicators provide insight on economic inefficiencies but do not drive water allocation.

The simulation approach that is proposed is conceptually simple. It consists of three steps:

1. *Setting-up a simulation model of water management in the basin*, in which all the relevant components (surface and groundwater resources, infrastructure, demands, etc.) are included. The model must be capable of reproducing current water allocation rules, representing different management policies, integrating legal aspects, institutional issues, etc.

2. *Economic assessment of the resource allocation undertaken by the base model.* This assessment requires economic function (e.f.) for the different elements modelled, representing the unit cost/benefit that flow, storage or supply to each element generate in the system. For example, the e.f. will be a demand curve for the uses, a cost function for pumping, ... The simulation of the system for a given hydrologic scenario is named as the Base Case.

3. *Use of specific routines for the sequential and iterative use of the previous models to obtain the resource costs, based on previous definitions.* A modified case corresponds to the simulation with the same hydrologic scenario and a perturbation consisting in adding (or removing) a differential water volume (ΔVolume) at the location and time of interest. Thereafter, the model carries out a new resource allocation, using the allocating rules, and after that, the total economic benefit of this modified case is evaluated. The difference in total benefit from the base to the modified case (ΔBenefit) is computed. The ratio ΔBenefit/ΔVolume is an approximation of the aggregated MROC for the system, and reflects the aggregated economic cost of water scarcity, according to the existing allocation criteria.

In the same way, by assessing the economic impact of a differential perturbation of the environmental constraints (like minimum streamflow, minimum reservoir storage, ...) we can estimate an approximation of the marginal cost of the environmental requirements, MOCER.

V.A. Tools for the economic analysis integrated in a Decision Support System (AQUATOOL)

The integrated hydro-economic model can be developed "ad-hoc" for a specific system, or we can resort to the use of generic tools integrated in Decision Support Systems (DSS). New modules have been integrated in the DSS AQUATOOL, incorporating tools to apply the proposed methodology.

AQUATOOL (Andreu et al., 1996) is a generalized DSS for integrated water resources planning and management, including conjunctive use of surface and groundwater. Computer-assisted design modules allow any complex water resource system to be represented in a graphical form, giving access to geographically referenced databases and knowledge bases. The modelling capabilities include basin simulation and optimization modules, and aquifer flow modelling module, and two modules for risk assessment.

Several tools have been developed to perform the calculations described in the precedent section (Collazos, et al., 2004). The preparation of a simulation model is already accomplished in many of the River Basin Agencies in Spain, due to the planning tasks undertaken for the elaboration of the Basin Hydrological Plans. For example, in the Jucar Basin Agency a model is available, which has been implemented and successfully applied using the simulation module SIMGES of AQUATOOL. SIMGES is a generic model (it can be used to represent any basin), which allocates water period by period, based on the priorities assigned by the modeller to the elements of the systems, respecting physical and operative constraints. Routines in MEvalGes have been implemented to carry out multiple simulations tasks for each of the points or elements of the basin selected and for all the months in the hydrologic scenario. A friendly graphic user interface, GESTAL, has been developed to facilitate the use of MEvalGes (Fig. 4).

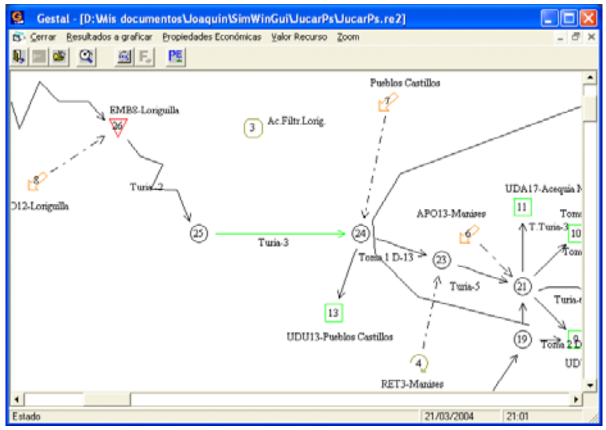

Fig. 4. Main window of GESTAL

V.B. Application to the Júcar Pilot River Basin

The Júcar River Basin (Eastern Spain) is the Spanish pilot basin in the implementation of the WFD. The Júcar River Basin Agency has recently released a provisional Art. 5 Report (http://www.chj.es/cpj3/imagenes/Art5/Articulo_5_completo.pdf). The approach described in this paper is currently being applied to the Júcar River Basin District (RBD). An integrated river basin simulation model had been developed using AQUATOOL (Fig. 5).

The Júcar River, 512 km long, is the main river in the District. This river presents different types of stretches along its course according to the orography: from the Iberian Mountain system, through the La Mancha plateau, and finally to the coastal plain. The main reservoirs are Alarcón (1112 Hm^3), Contreras (852 Hm^3) in its main tributary (the Cabriel River), and Tous (370 Hm^3), which defines the last reach of the river before flowing into the Mediterranean Sea. Groundwater resources account for about a 50% of the available resources in the basin (2384 Hm3), although it is necessary to take into account the relation with the surface bodies and the overexploitation of some hydrogeological units. The overexploitation of the Mancha Oriental aquifer produces a significant reduction in the river baseflow. The Canal Júcar-Turia connects the Júcar and Turia rivers and it is used for public water supply and irrigation. The Acequia Real del Júcar (dated from the XIII century) distributes water for irrigating mainly orange trees and rice fields in the final reach of the Júcar River. Irrigation is the main use in terms of water consumption (about 87%). Two irrigation areas can be defined: downstream Tous dam (with fruit trees, rice and orchard crops) and the zone of Albacete, in La Mancha plateau, with extensive farming (mainly cereals and oleaginous plants). Production functions and water demand functions have been characterized for the different Agricultural Demand Units according to the type of crops. Urban demand curves have been also estimated for the main cities in the Basin.

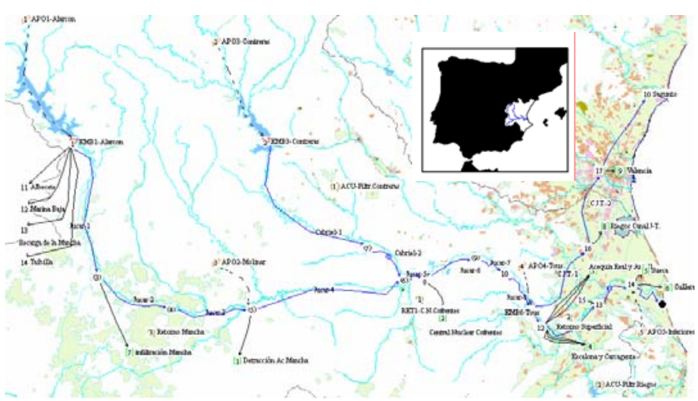

Fig. 5. Location and schematic of the Júcar River Basin

Results obtained so far are showing consistency with the expected economic behaviour. For instance, opportunity cost of the resource at the Tous reservoir is higher in water scarcity situations, and lower in abundance situations (Fig. 6). The maximum MROC (higher than 0.7 €/m^3) corresponds to the drought episode of 1994-1995, and is related with important shortages in the supply to the agricultural and urban sectors. Opportunity costs are modified in time when there is the possibility of storing water in a reservoir.

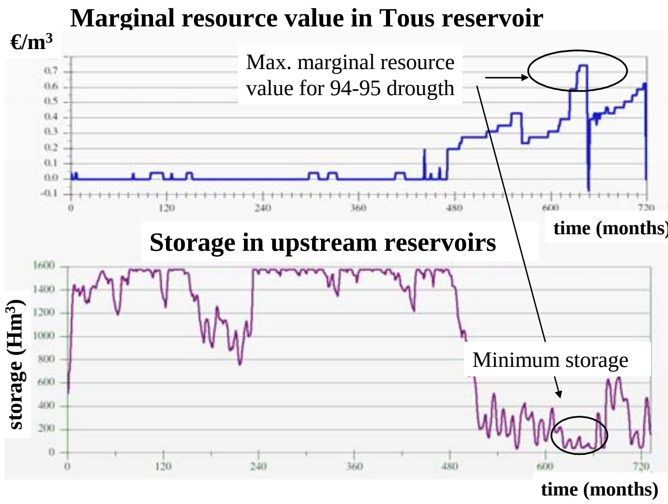

Fig. 6. Location and schematic of the Júcar River Basin

Opportunity costs are modified in time when there is the possibility of storing water in a reservoir, as it is shown in Fig. 7 by comparing the MROC at the head of the reservoir and downstream, at the Sueca intake, in the last reach of the river (without storage capacity). The storage capacity contributes to smooth the temporal distribution of the MROC.

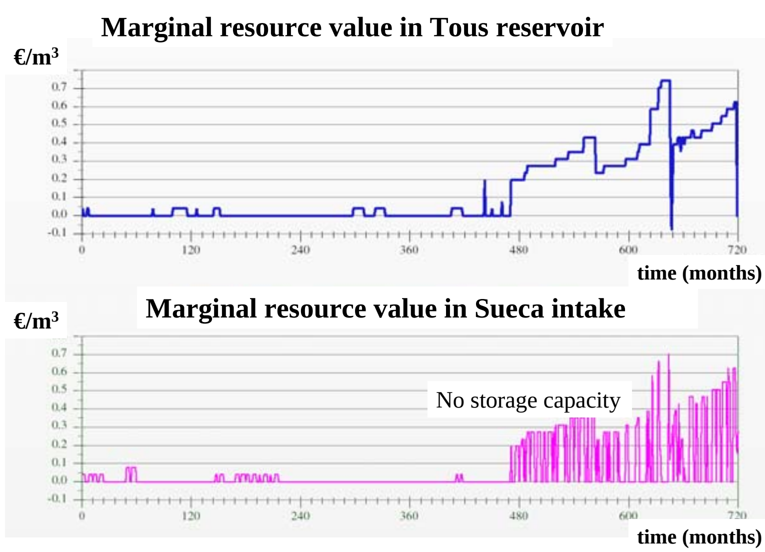

Fig. 7. MROC with and without storage capacity

VI. Conclusions

Hydro-economic models provide a tool for a systematic assessment of two complementary measures of the resource opportunity cost and the opportunity cost of the management measures required to achieve the environmental objectives (eg., minimum streamflow) in a water resources system. Theses values, which change dynamically in space and time, can served as indicators from which we could infer components of the resource and environmental costs required by the WFD. The development of tools integrated within a DSS facilitates its application to different river basins, especially if a validated simulation model is available, as it happens in many Spanish river basins.

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Acknowledgments

The research presented in this paper has been developed for the Jucar River Basin Agency (under the direction of Teodoro Estrela) and the Spanish Ministry of Environment (under the direction of Josefina Maestu), and it is partially funded by a research project ("Desarrollo y aplicación de metodologías y herramientas en la Cuenca Piloto del Río Júcar para los Análisis Económicos requeridos en la Directiva Marco europea del Agua") commissioned to the consultant company EPTISA.