Design of efficient water pricing policies integrating basinwide resource opportunity costs

Pulido-Velazquez, M.[1], Alvarez-Mendiola, E.[2], Andreu, J.[3]

ABSTRACT

By ignoring the opportunity cost of water use, water is undervalued, which can lead to significant errors in investments and water allocation decisions. The marginal resource opportunity cost (MROC) varies in time and space, as resource availability, demands, and users' WTP vary. This spatial and temporal variability can only be captured by basinwide hydro-economic models integrating water demands and environmental requirements, resources, infrastructure, and operational and institutional restrictions. This paper presents a method for the simulation of water pricing policies linked to water availability, and the design of efficient pricing policies that incorporate the basinwide marginal value of water. Two approaches were applied: priority-based simulation and economic optimization. The improvement in economic efficiency was assessed by comparing the results from simulation of the current system operation and the pricing schedule. The difference between the benefits for the simulated current management and the upper bound benefits from optimization indicates the maximum gap that could be bridged with pricing. In the application to a synthetic case, a storage-dependent step pricing schedule derived from average MROC values led to benefits that capture 80% of the gap of net benefits between management without pricing and the economically optimal management. Different pricing policies were tested, depending not only on reservoir storage but also on previous inflows. The results show that the method is useful for designing pricing policies that enhance the economic benefits, leading to more efficient resource allocations over time and across the competing uses.

Keywords: Water pricing; River basin management; Optimization; scarcity pricing; opportunity cost

1. Associate Professor, Research Institute of Water and Environmental Engineering (IIAMA). Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain. Email: mapuve@hma.upv.es
2. Profesor-Investigador, Centro de Investigaciones del Agua-Querétaro, Facultad de Ingeniería, Universidad Autónoma de Querétaro, Querétaro, México. Email: almendi@uaq.mx
3. Professor, Research Institute of Water and Environmental Engineering (IIAMA). Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain. Email: ximoand@upvnet.upv.es

INTRODUCTION. WATER OPPORTUNITY COST

Of all the tools available for solving water scarcity problems, better pricing is probably the most underutilized relative to its potential (Griffin 2006: 269). That water is often underpriced is widely evident: quantity demanded frequently exceeds supply, often leading to a nonsustainable use of the resources. Properly managed, this instrument has the potential to promote improved economic efficiency (Rogers et al. 2002). Several international institutions have recently promoted the application of the principle of full cost recovery and many countries are now engaged in some form of pricing reform (OECD 1999, Dinar 2000). One recent institutional attempt to design an efficient pricing system is the EU Water Framework Directive (WFD, European Commission 2000). The WFD requires the implementation of a pricing policy that provides incentives for efficient water use, contributing to the environmental objectives (a good water status for all natural water), and ensures an adequate contribution of the various water uses to the recovery of water service costs. The design of methods for implementing those principles has produced considerable debate (WATECO 2002; Heinz et al. 2007; Iglesias and Blanco 2008).

The cost of water has two broad components: the cost of its provision and its opportunity cost, or the value of the forgone option resulting from a water management/allocation decision. There is always an opportunity cost if there is water scarcity, either in quantity or quality, since its use involves a sacrifice to alternative uses. From the point of view of managing water as an economic resource, the key challenge is to ensure that this cost is considered in resource allocation decisions (Griffin 2001). Users should get a signal of water's opportunity costs so that they behave accordingly. By ignoring this resource opportunity cost, water is undervalued, which can lead to significant errors in investments and water allocation among users. When the price of water reflects its marginal cost, the resource will be put to its highest-valued uses and an optimal resource allocation would be reached, for which the marginal productivity of water would be equal across the different uses and over time and society's economic welfare would be maximized. Despite the apparent simplicity of the concept, measuring the opportunity costs of scarce water is difficult. Since water markets are usually absent or inefficient, scarcity values go frequently unrecognized, and the assessment of these opportunity costs requires a systems approach and a proper method to estimate the value of water for the different users in the system to develop shadow prices reflecting the value of water (Young 2005: 15; Pulido-Velazquez et al. 2008). Scarcity values in water use can arise at the spatial scale, from intersectoral competition at a certain time (i.e., from economically inefficient spatial allocation of scarce existing resources) or at the temporal scale, by inefficient water allocation over time (when making decisions on the use of a certain water stock now or in the future). The term "*marginal user cost*" has been also applied in the economic literature of depletable resources to refer to the discounted value of sacrificed future uses (Tietenberg 2000:90; Griffin 2001): there is a trade-off between current and future net benefits. In addition, when infrastructure capacity is binding, there is a third opportunity cost to contemplate: the marginal capacity cost. Turvey (1976) defined the "marginal capital cost of water supply" as the cost savings from postponing a capacity addition scheme. Newlin et al. (2002) and other subsequent applications of the CALVIN hydro-economic optimization model (e.g., Jenkins et al. 2004; Pulido-Velazquez et al. 2004; Medellin-Azuara et al. 2009) have analyzed the marginal value of additional water supplies and infrastructure using an spatially intense model of water allocation in the intertied water supply system of California.

An optimal pricing scheme under the goal of deriving the greatest value from scarce water should include not only the marginal cost of water supply, but also the three components of the "nonaccounting" opportunity costs: the basinwide marginal value of water at the source, the "marginal user cost" or opportunity cost of water use over time, and the marginal capacity cost from limited infrastructure (Griffin 2001). Since opportunity cost depends on the alternative uses, an integrated basinwide approach is needed to account for all major competing water uses in the basin. This paper presents a new method for the simulation of different water pricing policies linked to water availability (or relative scarcity) in the basin, and the design of efficient water pricing policies that incorporate the marginal basinwide value of the resource. The approach is based on the systematic assessment of the basinwide marginal resource opportunity cost of water (MROC), an indicator of the aggregated economic impact of water scarcity and how much the users would be willing to pay (WTP) to mitigate that scarcity. The MROC varies dynamically in time and space, as resource availability, demands, and users' WTP vary. This spatial and temporal variability can only be captured by basinwide hydro-economic models integrating water demands, resources, and infrastructure, and operational and institutional restrictions.

ASSESSMENT OF THE MARGINAL RESOURCE OPPORTUNITY COST (MROC)

The EU WFD integrates economics into water management and policy making. According to the Directive, Member States must implement a pricing policy that provides adequate incentives for efficient water use and ensures adequate contribution of the different water uses to the recovery of the cost of water services, including ***environmental and resource costs***. Despite its key role in the design of such a pricing policy, the definition and assessment method of resource and environmental costs remains controversial and is one of the main issues regarding the implementation of the WFD that requires further methodological development (WATECO 2002;

Brouwer 2004; Heinz et al. 2007).

Pulido-Velazquez et al. (2006) proposed the term ***marginal resource opportunity cost*** (MROC) at a specific location and time to refer to the systemwide cost or forgone net benefit of having available one additional unit less of resource at that location and time. This shadow value varies dynamically in time and space, and represents the marginal economic value of natural (raw) water at the source, considering the intersectoral competition of water allocation in space and over time. Its assessment requires to simultaneously consider the value of water for all alternative water uses in the basin, as well as the system's variable operating costs. For that purpose, an integrated basinwide hydro-economic model is needed. Integrated hydro-economic models have to be capable to properly reproduce the physical behavior of the system, with a realistic representation of the spatial and temporal variability of surface and groundwater resources, while simultaneously incorporating the value of water for the different alternative uses in the basin (Lund et al. 2006; Harou et al. 2009).The results of these models capture the spatial and temporal variability of supply and demands, taking into account resource availability, storage capacity, losses, return flows, and marginal WTP or economic value at each water use, as well as the operation of the infrastructure. This representation allows the dynamic assessment of the marginal economic value of water (or MROC) at different locations in the basin (Newlin et al. 2002; Fisher et al. 2002; Pulido-Velazquez et al. 2004, 2006, and 2007). Two complementary approaches can be followed for analyzing water management in a water resource system: simulation and optimization. By defining the objective function as the total net benefit from water allocation, the ***optimization approach*** obtains the MROC as the shadow prices of the optimization; these results correspond to the economically optimal water allocation. On the contrary, the ***simulation approac*****h** assumes that the system is managed according to a set of operating rules and constraints that represents the current modus operandi of the system.

MROC assessment using priority-based Simulation

As competition for water resources increases, so does the need of an institutional framework governing regional water allocation. Institutional criteria are often more influential than physical or economic factors in determining flow allocation among uses. This ''institutional framework'' often refers to water use priorities as specified by the existing water-rights structure (Israel and Lund 2000). However, water rights are not necessarily the only prioritized water uses in a system, but also other uses as environmental or recreational uses can gain this stature.

Simulation or descriptive models are often the best approach for assessing the system performance for alternative strategies ("what if" scenarios), permitting a more detailed and realistic representation of the complex characteristic of a river system. In the simulation approach, water is allocated in accordance with a set of operating rules and priorities, which are defined with the aim to reproduce the current institutional framework in modelling efforts. Multi-period simulation models utilize optimization (often network flow programming) for determining operating decisions at each time step (e.g., Sigvaldason 1976; Labadie 1995; Andreu et al. 1996; Wurb 2005). Unlike multi-period optimization models, the simulation models can reproduce the actual operating rules of the system with reservoir releases based on existing storage without anticipating future inflows (avoiding the perfect foresight issues inherent to multi-period optimization), and replicate water allocation decisions based on water rights and priorities. This is usually accomplished by introducing certain unit cost coefficients that preserve priority ranks (Israel and Lund 2000). Unlike the optimization approach, the economic indicators provide insight on economic inefficiencies but do not drive water allocation. These models are better suitable to reproduce the modus operandi of the system under the current institutional setting.

The marginal economic value of raw water (or MROC) can be determined in simulation by assessing the impact on water use of a small change in streamflow, and then applying economic value estimates to the water use changes (e.g., Brown 1990; Pulido-Velazquez et al. 2006). The simulation approach that we propose is conceptually simple and consists of three steps:

- *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 allocation rules and modus operandi.
- *Economic assessment of the resulting resource allocation determined by the model*. This assessment requires economic functions for the different modeled elements, representing the unit cost/benefit that flow, storage or delivery to each element generate. The simulation of the system for a given hydrologic scenario is named as the Base Case.
- *Use of specific routines for the sequential and iterative use of the previous models to obtain the resource costs*. A Modified Case corresponds to the simulation with the same hydrologic scenario and a perturbation by adding (or removing) a differential water volume (ΔVolume) at the location and time of interest. Thereafter, the model reallocates the resource over time and space, using the operating rules, yielding a new economic benefit. The difference in total benefit between the Base and 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 with the existing allocation criteria.

Hydro-economic models can be developed "ad hoc" for a specific system or using generic Decision Support System (DSS) tools. AQUATOOL is a generalized DSS for integrated water resources planning and management, including conjunctive use of surface and groundwater. Computer-assisted design modules allow to represent any complex water resource system in a graphical form, giving access to geographically referenced databases and knowledge bases. New modules of the DSS AQUATOOL (Andreu et al., 1996) add tools for the economic assessment of water management in the system (Collazos, 2004; Andreu et al. 2005; Pulido-Velazquez et al. 2008). Hydro-economic simulation in DSS AQUATOOL is performed in 2 steps:

- First, the priority-based simulation module of AQUATOOL (Simges) is used to calculate monthly water allocation time series, and determine deliveries to the demands, deficits, and reliability of meeting each demand and environmental flow requirements.
- Secondly, the economic simulation module, EcoWin, is used to assess the benefits and scarcity costs (or economic losses) at each demand and aggregated for the basin, based on economic demand curves and operating costs. The iterative procedure mentioned above is then used to compute the MROC from simulation

The MROC obtained by the iterative simulation procedure described represent a first approximation to the marginal value of water in the system in that location over time. In the case of simulation, these values are conditioned to certain operating rules and priorities in the target demands that determine water allocation at each time step. It represents a positive (descriptive) valuation of the MROC corresponding to a certain modus operandi of the system.

MROC assessment using Economic Optimization

In an ***optimization model***, the optimal values of the dual variables, Lagrange multipliers, or shadow prices reproduce directly the change in the optimal value of the objective function as a consequence of a marginal change in the corresponding constraint. If the objective function represents the basinwide net benefit from water use, the shadow prices associated with water balance constraints at certain storage nodes of the flow network of the system (reservoirs, aquifers) provide the net benefit derived of a unit increase of the resource in that node at that time (or equivalently, the amount that the system is WTP for one additional unit of water at that moment and location). Thus, the optimization model provides time series of the marginal value of water at certain locations in the system, taking into account system-wide effects. The economic value of water will change over time and space depending on water scarcity and water demands.

The resulting MROC can be used to obtain an indicator of the resource/scarcity opportunity cost (Pulido-Velazquez et al. 2006 and 2008; Heinz et al. 2007). According to the economic theory, an optimal efficient water pricing policy would have to include this resource opportunity cost component, so that signals of water scarcity and the resource value are sent to the users. Since the MROC is calculated for the economically optimal system operation, these values represent the maximum (ideal) marginal economic value of one additional unit of water in the reservoir for the users in the system. This shadow value is thus equivalent to the maximum price that users at that location who value additional water the most would just be WTP for an additional cubic meter of water, given the optimal flows of the model solution (Fisher et al., 2002). Unlike the case of simulation, this MROC value corresponds to a normative valuation: the results from the optimization model indicate the maximum attainable economic efficiency. The distance between the benefits from the simulated current management and the maximum benefits obtained from optimization indicates the maximum profit gap that could be bridged with pricing policies.

There is also certain disturbing effect from optimization. The system operation is optimized for long hydrologic times, what means that the optimization is performed with perfect knowledge of future hydrology, what is known as the “perfect foresight” issue (Labadie 1997). The perfect foresight inherent to the deterministic optimization procedure overestimates the efficiency attained, representing an ideal upper bound of what can be achieved with realistic hydrology forecasts (Draper and Lund 2004). Perfect foresight can understate the value of new storage and conveyance capacity and underestimate actual scarcity and scarcity cost (Pulido-Velazquez et al. 2004, 2008). But the effects of perfect foresight on the overall performance of the system can be small when improved performance comes predominantly from consistent operation and allocation changes that do not require hydrologic foresight (Newlin et al. 2002).

METHOD AND TOOLS FOR DESIGNING EFFICIENT PRICING POLICIES INCLUDING BASINWIDE MROC

The resulting time series of MROC at the main reservoirs of the system can be used as the starting point for the design of basinwide efficient water pricing policies integrating marginal resource (scarcity) opportunity costs. When there is a reasonable correlation between reservoir storage and MROC at the reservoir, a step pricing schedule can be derived from average MROC values for different storage volumes. In this way, the price represents the average marginal opportunity cost of water use related to certain water availability in the system. The proposed methodology is based on the combined use of simulation and optimization hydro-economic models at the basin/water resource system scale. The method involves the following steps:

1) *Setting-up a simulation model of water management in the basin*. This model should integrate resources, demands, and infrastructure, with a realistic representation of the legal, institutional, environmental, and operational constraints. Once a conceptual model of the system is developed, some key inputs are: configuration of the flow network, facility capacities and operating rules, surface hydrology (represented by long inflow time series), losses and return flow equations, aquifer dynamics and stream-aquifer interaction, environmental water requirements (often imposed as instream flow constraints), and water demands (as fixed supply targets to be satisfied).
2) *Economic characterization of the system.* Hydro-economic models require empirically estimated marginal supply cost and benefit functions (or demand curves) for each alternative water demands/uses at the basin (Harou et al. 2009).
3) *Priority-based simulation of water management in the system.* In river basin models, water flow is basically simulated over space and time through mass balance or continuity equations at the nodes with (reservoirs, aquifers) or without storage capacity. The simulation will yield time series of flow, storage, delivery and water supply deficit (convertible into scarcity costs) and reliability for all the system over the simulated time horizon. Herein, scarcity cost at each water use (demand) is defined as the benefit forgone when deliveries are less than the maximum demanded by each user (Newlin et al. 2002; Pulido-Velazquez et al. 2006).
4) *Calculation of the time series of MROC at the main reservoirs of the system using simulation.* The MROC at the reservoirs is obtained by applying the iterative procedure previously described.
5) *Setting an economic optimization model for the system.* In this case, the objective will be to maximize the aggregated net benefit from water use over the optimization time horizon, subject to the physical, environmental, institutional, and operational constraints.
6) *Economic optimization of water management in the system.* The optimization will yield time series of flow, storage, delivery and water supply deficit (convertible into scarcity costs) for all the system over the optimized time horizon.
7) *Calculation of the time series of MROC at the main reservoirs of the system by optimization.* The shadow value associated to the reservoirs' mass balance equations directly provides MROC times series in optimization.
8) *Analysis of net benefits and MROC from simulation and economic optimization.* The distance between the benefits from simulation with the current management and the

maximum benefits obtained from the optimization indicates the profit gap that can be bridged by the pricing policies.

9) *Proposal of pricing policies based on simulation/optimization MROC.* A storage-dependent step function is obtained by sorting and averaging the MROC values at different storage intervals for a certain reservoir in the system. Other different pricing policies are also tested.

10) *Simulation of economic results for different pricing policies.* Improved aggregated economic efficiency resulting from the application of pricing policies is assessed by comparing the results obtained by simulating the current operation of the system with those obtained with the simulation of the pricing policy. The use of simulation for assessing the efficiency improvements from the tested pricing policies avoids the perfect foresight issue inherent to multi-period optimization models (as discussed in the previous section). The results from the optimization model indicate the maximum attainable economic efficiency.

It is assumed that users react to price changes according to microeconomic theory, either as profit-maxing producers or as utility maximizing consumers. The change in water use for a change in price will be given by the corresponding demand (marginal benefits) functions (point 2). When water reserves in the system are scarce, a high price in the step-pricing function will lead to a reduction in the target demand for each use. In this way, the step-pricing function will act as a kind of system operating rule, in which reservoir releases are modified through variations in the quantity demanded (the target demand of the simulation model) under scarcity conditions. The reduction in the quantity demanded will be not equal across uses, but it will rather vary according to each demand curve, so that the reduction will be greater in percentage terms for the low-value uses. This will ensure than, when water is scarce, it will be mainly used by the high-value uses. The temporal dimension of water opportunity cost is also implicitly considered in the time series of MROC, and so, it is somehow embedded into the design of the pricing policy.

The practical implementation of this method was done with the coordinated use of different modules of the generalized DSS AQUATOOL. The priority-based simulation module, SIMGES, was used to simulate the basinwide effect of the pricing policy on the time series of storage, flow, supply, and deficit of supply. The model applies an optimization algorithm to deal with monthly decisions of water allocation among the different competing uses, minimizing the weighted deviations from the target. The weights are defined consequently with the priorities given to each demand (Andreu et al. 1996). The economic postprocessor, ECOWIN, then uses the operating cost and demand functions to convert the time series of water delivered into net benefits and scarcity costs for each demand and aggregated for the whole system. The storage-dependent step pricing policy is simulated in SIMGES by translating the level of water usage restrictions at each level of price into a coefficient of restrictions to be applied to each target demand depending on the status of reservoir storage at the beginning of each simulation period.

APPLICATION

A simple synthetic case study has been used to illustrate the method. The system is made up of a reservoir and 2 demands (A and B) competing for a scarce resource (Fig. 1), with demand A with the highest priority of supply (this could be the case of urban vs. agricultural demand, or two irrigation demands with different priorities). The reservoir has a useful storage capacity of 93 Mm^3 (millions of cubic meters) and dead storage of 2 Mm^3. Fig. 2 shows the 55-year monthly inflow time series. The use of long natural inflow time series allows taking into account the temporal variability of the hydrology, including periods of low flow/droughts and high flow distributed over time as happened in the past. The economic demand curves are depicted in Fig. 3 (assuming linear demand curves). B is the use with the highest economic value (for a given supply deficit, scarcity cost will be higher in use B) but with less priority of supply.

Priority-based simulation and economic optimization models

Once the simulation model is implemented using the simulation module of the DSS AQUATOOL (step 1, previous section), water management is simulated with water allocated to each demand in priority order (i.e., first, water is allocated to demand A, and from the remaining storage, to B). Simulation results include water supply reliability indices, flow, delivery, and storage time series and other summary statistics (step 3). Scarcity (water supply deficit) and scarcity costs (forgone net benefits) are calculated over time per demand and aggregated for the whole system, based on the economic demand curves (step 2) and the time series of deliveries. The economic module of AQUATOOL, EcoWin, is then used to obtain the marginal economic value of water at the reservoir (MROC time series, Fig. 4) for simulation (step 4). Fig. 4 shows that, in agreement with the economic theory, the greatest MROC corresponds to the periods in which the reservoir is at a minimum (at the dead storage). On the contrary, the marginal value of water becomes zero when the reservoir is at full capacity (no water scarcity).

The non-linear economic optimization model has been implemented using the optimization package GAMS (General Algebraic Modeling System) (Brooke et al. 1998). The economic optimization model (steps 5-6) maximizes the aggregated net benefit from the two demands (or what is the same, minimizing scarcity plus variable operating costs) over the time horizon. Scarcity costs are found by integrating the demand curves from the maximum demand leftward to the delivery. The model involves constraints for the maximum and minimum (dead pool) storage capacity, the minimum environmental instream flow in the last reach of the river, the mass balance equation at the reservoir, and the mass balance at the delivery node.

Fig. 4 depicts the marginal economic value (MROC) time series at the reservoir for optimization (step 7). The MROC curve for optimization is more regular and smooth than the one for simulation, since optimization better allocates water over time reducing the periods of severe scarcity. The total net benefit is greater for optimization than for simulation (Table 1), given the optimal water reallocation from use A (higher priority) to use B (higher economic value). The optimization model significantly reduces the deficit to B and the maximum deficit values for A. Part of the increase in the total benefit is also due to the optimal management of the system over time, what allows to significantly reduce the scarcity costs during the main drought events (since scarcity cost increases non-linearly with the deficit). The distance between the benefits from simulation with the current management and the maximum benefits obtained from optimization, in this case, 2.2 M€/year, indicates the profit gap that can be bridged with pricing policies.

Storage-based step pricing function

Fig. 4 represents the MROC and storage time series at the reservoir for simulation and optimization. The MROC varies over time depending on the relative scarcity in the system (available resources and demands), but also on the future status of the system. The same storage does not imply the same MROC, since the value of water also depends on the coming inflows and future scarcity conditions. An additional unit of water will be used over time according to the priorities in Simulation, and to the economically optimal operation in Optimization. The objective is to derive a practical pricing policy using this information (step 9), and to value the gains in terms of net benefits (step 10). For that purpose, the average MROC values for different storage intervals are computed, and then used to derive the step pricing schedule, following the procedure laid out in Fig. 5. In this case, the averaged MROC pricing levels for the Priority-based Simulation are higher than for Optimization, what it is consistent with the fact that the economic optimization reduces scarcity costs, leading to a lower marginal value of additional water. The effect of the pricing schedules derived from the Simulation and the Optimization MROC and storage time series (Fig. 6) were then simulated by imposing changes in the demanded quantities at each use according to the demand curves. The results (see Table 2) indicate that the step pricing schedule derived from average MROC values from simulation leads to economic benefits that already capture 80% of the gap of total net economic benefits between management without pricing (based on priorities) and the economically optimal management. By applying the storage-based pricing functions, the system penalizes water use B and allocates more water to use A (with higher economic values). In this case we obtained lower total net benefits in the pricing policy derived from the economic optimization's averaged MROC.

Optimized storage-dependent step pricing

An alternative for defining an efficient policy would be to optimize the price levels at each step so that the total net economic benefit of water use is maximized ("optimal" step pricing policy). For that purpose, the prices were optimized with non-linear programming, using as starting values the prices from the averaged MROC values. Fig. 6 shows that the optimal step pricing policy is closer to the one from MROC-simulation than to MROC-optimization, what confirms the fact that better economic results were obtained using the former pricing policy. Other basinwide pricing policies have been also tested with the aim of better approximate the variability of the MROC time series using different explanatory variables.

Step pricing depending on previous inflows

The MROC at a certain location and time depends not only on water availability (storage) in the system, but also on the coming reservoir inflows and the evolution of the scarcity conditions. In order to introduce this in the design of a pricing policy, the last-year annual inflow to the reservoir was included in the definition of the step pricing function, using the averaged MROC-optimization as the starting point. Analyzing the droughts in the historical inflow time series through the "run theory" (Dracup et al. 1980) with the mean annual inflow as the threshold, ten droughts events were found during the historical period, with an average duration of 3.1 years. Most drought episodes are multiannual, what corresponds to a time series with a significant autocorrelation over time. Close to the mean magnitude of the droughts, 100 Mm^3 was used as the lowest threshold for the inflow categorization, and the MROC values from optimization were averaged for each inflow interval. The resulting inflow-dependent pricing function (Fig. 7) was tested and compared against the other pricing policies.

Annual constant pricing policy depending on initial storage and previous annual flow

The information provided by the previous inflows and the status of the system reserves can be used as a tool for predicting future flows and drought forecasting, in order to achieve an efficient hedging operation of the reservoirs with anticipation to droughts (Ochoa-Rivera et al. 2007). To include this issue in the design of an efficient pricing policy, the pricing steps were defined as dependent on the annual inflow in the first and even the second previous year and the available storage at a certain month, according to the following equation:

$$p_{year(t)} = a + b \cdot V_{oct} + c \cdot Q_{year(t-1)} + d \cdot (Q_{year(t-1)} + Q_{year(t-2)}) \quad (1)$$

where p_{year} is the constant price for that year, V_{oct} is the initial storage for October (the starting of the irrigation season), Q_{year} are the inflow values in the last and the year before the last, and a, b, c, and d are parameters calibrated so that the time series of the resulting prices gets as close as possible to the MROC time series.

Seasonal pricing depending on initial storage and previous annual flow

With the purpose of reflecting the variation of the MROC for the same storage volumes depending on whether scarcity is growing or decreasing over time, the price has also been dependent on the previous status of the system in the precedent seasonal period. The adjusted functions are:

$$p_{oct\text{-}april} = a + b \cdot V_{oct} + c \cdot Q_{apr,year(t-1)} \quad (2)$$

$$p_{apr\text{-}sept} = d + e \cdot V_{apr} + f \cdot Q_{oct,year(t-1)} \quad (3)$$

where $p_{oct\text{-}april}$ and $p_{april\text{-}sept}$ are the seasonal prices, V_{apr} is the initial storage for April and V_{apr} for October, $Q_{apr,\ year(t-1)}$ and $Q_{oct,year(t-1)}$ are the inflow values corresponding to the last April and October, and a, b, c, d, e, and f are parameters calibrated to approximate the MROC time series.

Testing price efficiency with synthetic inflow time series

Although it is usual to adopt a deterministic approach in the analysis of water resource systems and simulate for the historical flow records, these series represent just a single realization of the infinite number of likely future hydrologic scenarios. But the future sequence of flows will not be the historical one. The generation of multiple synthetic hydrologic time series that statistically resemble the historical one allows us to address the issue of uncertain future inflows by providing a broader range of equally likely flow sequences for testing alternative policies. The use of synthetic streamflows improves the precision with which performance indices can be estimated; this is particularly useful for water resources with large amounts of over-year storage (Loucks and van Beek 2005). Fifty synthetic time series have been generated using a classic stochastic ARMA model and applied to test whether the resulting benefits (averaged through the synthetic scenarios) were consistent with the value for the historical record.

RESULTS AND DISCUSSION

In this particular case, the step pricing function derived from the averaged MROC-Simulation for each storage interval leads to total benefits quite close to those from the economic optimization

(Table 2). The simulation of this pricing policy indicates an increase in economic benefits that capture 80% of the gap of total net benefits between management without pricing and the economically optimal management. Although these pricing policies were derived from the average values of MROC at each interval, other statistical measures of central tendency (e.g., the mode, the median) could be tested. The step pricing function derived from the averaged MROC from optimization (shadow values) led to a lower economic efficiency. The optimized storage-dependent step pricing did not improve much the economic efficiency either. Thus, the MROC time series at the reservoir has been useful for designing an economically efficient basinwide water pricing policy. For this particular example, despite the advantage of the practical simplicity of an annually constant pricing policy at the beginning of the hydrological year and the security for the users' decisions, total net benefits are not as high as the ones corresponding to the storage-dependent pricing policy. The two seasonal pricing functions depending on both inflow and storage yielded almost the same benefit, but in any case, lower than for the storage-dependent step pricing. The long persistence of the historical flow time series (Fig. 2) produces long over-year droughts, so that the seasonal variation is not so significant in terms of water scarcity. The inflow-dependent pricing function (classified by inflow thresholds) produced greater benefits than the priority-based simulation (actually, all pricing policies did, since these policies translate a component of the marginal opportunity cost into water management), but lower than for the storage-dependent step pricing.

From this analysis we can deduce some recommendations for designing efficient basinwide pricing policies. First, the MROC time series are calculated by simulating water management in the system with the existing operating rules (priority-based simulation). If possible, an optimization model can be implemented to maximize the economic benefit of water use in the basin over time and across the competing uses. The results of this model provide an upper bound of the benefit that can be achieved with an efficient pricing policy. Then, a step pricing policy is defined as a function of available storage, using average MROC values for the range of storage volumes of the corresponding step. By comparing the resulting total benefit from the pricing policy with the one corresponding to the economic optimum, the pricing policy can be proposed or further refined. The use of pricing policies depending on the previous status of the system or annual or seasonal price functions make the calculation more complex; in this particular case, these policies did not imply a substantial improvement of the benefits from water use. But this is only confirmed for this particular case, and it can be different in other cases. In any case, all these policies represent an increase in net benefits as compared to the traditional water allocation system based on priorities. Finally, multiple synthetic flow time series are used to check how robust the calculation of the expected benefits is.

SUMMARY AND CONCLUSIONS

This paper presents a new method for the simulation of different water pricing policies linked to water availability (or relative scarcity) in a river basin and the design of efficient water pricing policies including the marginal value of the resource at the basin scale, based on the use of basinwide hydro-economic models. Storage-based water pricing policies are simulated by dynamically changing the target demands according to the price level that corresponds to the storage at the reservoir. The design of efficient pricing policies is based on the assessment of the marginal resource opportunity cot (MROC) as the value for the system of an additional unit of water at a certain location and time. The MROC time series can be estimated for the existing priorities and modus operandi (priority-based simulation) or by the shadow values of the balance constraints when water is allocated to maximize the total net benefit in water use (economic optimization). The improvement in economic efficiency was assessed by comparing the results from the simulation of the current system operation and from the pricing schedule. The distance between the benefits from the simulated current management to the maximum benefits from optimization indicates the maximum profit gap that could be bridged with pricing.

In the application to a synthetic case, a step pricing schedule derived from average MROC values from simulation led to economic benefits that capture 80% of the gap of net benefits between management without pricing and the economically optimal management. Different pricing policies depending not only on storage but also on previous inflow have been tested. The relative efficiency of the different pricing policies depends on many factors inherent to the complexity of the system such as the economic demand functions, the time-dependent structure of the inflow time series and the statistical droughts properties, the configuration and infrastructure of the system, the regulatory capacity, etc. The results show that the method is useful for designing efficient pricing policies that enhance economic benefits and lead to more efficient resource allocations over time and across the different competing uses of the system. Even though the absolute increase in net benefits for the particular example presented is not so high, the method is totally generalizable and could yield much larger improvements in other water resources systems, especially when dealing with marked water scarcity conditions, competing uses with important differences in economic value, and significant economic inefficiencies derived from the existing water allocation policies.

Although economically efficient prices should incorporate the marginal value at the source (MROC), these prices are not necessarily the prices that water consumers should be charged. The final prices can be a matter of social or national policy (Fisher et al. 2002). Other important pricing goals apart from economic efficiency, as revenue sufficiency and neutrality, equity, or environmental sustainability should be also considered. The literature on the analysis of these pricing issues at the basin scale is still very scarce (Ward and Pulido-Velazquez 2008 and 2009). Environmental restrictions can be addressed by imposing minimum ecological flow constraints in the models and analyzing the implications for water pricing. Equity can be also addressed in different ways, although the extent to which water pricing methods can affect income redistribution is limited (e.g. Tsur and Dinar, 1995, for the agricultural sector). Measures taken to guarantee access to water should not be confused with income redistribution, a function that is typically reserved for the fiscal instruments, including general taxes (Griffin, 2001). From the different ways to promote equity, efficiency, and sustainability in water management, water pricing is probably the simplest conceptually, but maybe the most difficult to implement politically (Rogers et al. 1998).

Stochastic dynamic programming is an alternative for determining the marginal value of water in a reservoir (e.g. Tilmant et al. 2008), with the advantage over deterministic optimization techniques that it explicitly considers the effect of hydrologic uncertainty on the results. In this case, however, the aim was to develop a general method that can be applied in practice to any complex system with available generalized DSS tools. In this sense, most DSS tools are based on network flow optimization for dealing with multiperiod multireservoir large complex systems (eg, Labadie, 1995; Andreu et al., 1996; Jenkins et al., 2004). In any case, the "deterministic optimization" is used in our approach just to assess the efficiency gap between current management and perfect profit-maximizing water allocation and to help develop efficient water pricing policies based on average MROC (also alternatively developed with simulation MROC values). The effect of each pricing policy under uncertain future inflows is then assessed through simulation, avoiding the perfect foresight issue of optimization and obtaining more realistic costs and benefits. Given the unavoidable uncertainty regarding the different inputs of the model, the issue of the uncertainty associated with the model predictions about the impacts of the pricing policies would need to be further explored in a comprehensive way over a broad number of model inputs.

Some tools have been prepared for the practical implementation of the method with GAMS and new modules for the DSS AQUATOOL. River basin simulation models are already available in

AQUATOOL for several Spanish river basins, some developed in the context of the new River Basin Plans for the implementation of the EU WFD (Paredes-Arquiola et al. 2010). Once the economic characterization of water uses in the basin is available, the approach is ready to be extended to more complex real cases. For the practical use of the approach in the implementation of the WFD, further research is needed on issues as the contribution of pricing policies to the good status of water bodies (Riegels et al. this issue) and the integration of the financial, resource, and environmental components of the cost of water services.

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FIGURE CAPTION LIST

TABLES

Table 1. Benefits and mean annual deficits for simulation and optimization

Approach	**Benefit A** (M€/year)	**Benefit B** (M€/year)	**Mean total Benefit** (M€/year)	**Mean deficit A** (Mm^3/year)	**Mean deficit B** (Mm^3/year)
ECONOMIC **OPTIMIZATION**	25,49	28,05	53,54	10,85	2,94
PRIORITY-BASED S**IMULATION**	26,05	25,38	51,43	4,21	9,04

Table 2. Comparison of annual benefits for different pricing policies. Historical vs. synthetic inflow time series.

Approach	**Benefit A** (M€/year)	**Benefit B** (M€/year)	**Total Benefit *** (M€/year)	**Total benefit, synthetic** (M€/year)**
ECONOMIC OPTIMIZATION	25,49	28,05	53,54	53,99
PRIORITY-BASED **SIMULATION**	26,05	25,38	51,43	52,51
STORAGE-DEPENDENT STEP PRICING				
Based on MROC-SIMULATION	25,34	27,73	53,07	53,57
Based on MROC-OPTIMIZATION	25,78	26,90	52,68	52,46
Optimized storage-dependent step pricing	25,24	27,87	53,11	53,57
Inflow-dependent step pricing	25.60	27.11	52.71	52.91
ANNUAL CONSTANT PRICING				
Based on MROC-OPTIMIZATION	25,60	27,01	52,61	53,24
Based on MROC-SIMULATION	25,90	26,35	52,25	51,37
SEASONAL PRICING based on storage and previous inflows				
Based on MROC-OPTIMIZATION	25,71	26,91	52,62	53,31
Based on MROC-SIMULATION	24,76	27,58	52,34	53,00

* Based on the historical flow records   ** Average value across generated synthetic inflow scenarios