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Pulido-Velazquez, M.; Álvarez Mendiola, E.; Andreu Álvarez, J. (2013). Design of Efficient Water Pricing Policies Integrating Basinwide Resource Opportunity Costs. *Journal of Water Resources Planning and Management*. 139(5):583-592. doi:10.1061/(ASCE)WR.1943-5452.0000262.



The final publication is available at

[http://dx.doi.org/10.1061/\(ASCE\)WR.1943-5452.0000262](http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000262)

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1 **Design of efficient water pricing policies integrating basinwide resource opportunity costs**

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

3

4 ***ABSTRACT***

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

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

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25 **INTRODUCTION. WATER OPPORTUNITY COST**

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

39 The cost of water has two broad components: the cost of its provision and its opportunity cost, or
40 the value of the forgone option resulting from a water management/allocation decision. There is
41 always an opportunity cost if there is water scarcity, either in quantity or quality, since its use
42 involves a sacrifice to alternative uses. From the point of view of managing water as an economic
43 resource, the key challenge is to ensure that this cost is considered in resource allocation
44 decisions (Griffin 2001). Users should get a signal of water's opportunity costs so that they
45 behave accordingly. By ignoring this resource opportunity cost, water is undervalued, which can
46 lead to significant errors in investments and water allocation among users. When the price of
47 water reflects its marginal cost, the resource will be put to its highest-valued uses and an optimal
48 resource allocation would be reached, for which the marginal productivity of water would be
49 equal across the different uses and over time and society's economic welfare would be
50 maximized. Despite the apparent simplicity of the concept, measuring the opportunity costs of
51 scarce water is difficult. Since water markets are usually absent or inefficient, scarcity values go
52 frequently unrecognized, and the assessment of these opportunity costs requires a systems
53 approach and a proper method to estimate the value of water for the different users in the system
54 to develop shadow prices reflecting the value of water (Young 2005: 15; Pulido-Velazquez et al.
55 2008). Scarcity values in water use can arise at the spatial scale, from intersectoral competition at
56 a certain time (i.e., from economically inefficient spatial allocation of scarce existing resources)
57 or at the temporal scale, by inefficient water allocation over time (when making decisions on the

58 use of a certain water stock now or in the future). The term “*marginal user cost*” has been also
59 applied in the economic literature of depletable resources to refer to the discounted value of
60 sacrificed future uses (Tietenberg 2000:90; Griffin 2001): there is a trade-off between current and
61 future net benefits. In addition, when infrastructure capacity is binding, there is a third
62 opportunity cost to contemplate: the marginal capacity cost. Turvey (1976) defined the “marginal
63 capital cost of water supply” as the cost savings from postponing a capacity addition scheme.
64 Newlin et al. (2002) and other subsequent applications of the CALVIN hydro-economic
65 optimization model (e.g., Jenkins et al. 2004; Pulido-Velazquez et al. 2004; Medellin-Azuara et
66 al. 2009) have analyzed the marginal value of additional water supplies and infrastructure using
67 an spatially intense model of water allocation in the intertied water supply system of California.

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

83 **ASSESSMENT OF THE MARGINAL RESOURCE OPPORTUNITY COST (MROC)**

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

91 Brouwer 2004; Heinz et al. 2007).

92 Pulido-Velazquez et al. (2006) proposed the term *marginal resource opportunity cost* (MROC)
93 at a specific location and time to refer to the systemwide cost or forgone net benefit of having
94 available one additional unit less of resource at that location and time. This shadow value varies
95 dynamically in time and space, and represents the marginal economic value of natural (raw)
96 water at the source, considering the intersectoral competition of water allocation in space and
97 over time. Its assessment requires to simultaneously consider the value of water for all alternative
98 water uses in the basin, as well as the system's variable operating costs. For that purpose, an
99 integrated basinwide hydro-economic model is needed. Integrated hydro-economic models have
100 to be capable to properly reproduce the physical behavior of the system, with a realistic
101 representation of the spatial and temporal variability of surface and groundwater resources, while
102 simultaneously incorporating the value of water for the different alternative uses in the basin
103 (Lund et al. 2006; Harou et al. 2009). The results of these models capture the spatial and temporal
104 variability of supply and demands, taking into account resource availability, storage capacity,
105 losses, return flows, and marginal WTP or economic value at each water use, as well as the
106 operation of the infrastructure. This representation allows the dynamic assessment of the
107 marginal economic value of water (or MROC) at different locations in the basin (Newlin et al.
108 2002; Fisher et al. 2002; Pulido-Velazquez et al. 2004, 2006, and 2007). Two complementary
109 approaches can be followed for analyzing water management in a water resource system:
110 simulation and optimization. By defining the objective function as the total net benefit from water
111 allocation, the *optimization approach* obtains the MROC as the shadow prices of the
112 optimization; these results correspond to the economically optimal water allocation. On the
113 contrary, the *simulation approach* assumes that the system is managed according to a set of
114 operating rules and constraints that represents the current modus operandi of the system.

115 **MROC assessment using priority-based Simulation**

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

122 Simulation or descriptive models are often the best approach for assessing the system

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

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

- 141 • *Setting-up a simulation model of water management in the basin*, in which all the relevant
142 components (surface and groundwater resources, infrastructure, demands, etc.) are included.
143 The model must be capable of reproducing current allocation rules and modus operandi.
- 144 • *Economic assessment of the resulting resource allocation determined by the model*. This
145 assessment requires economic functions for the different modeled elements, representing the
146 unit cost/benefit that flow, storage or delivery to each element generate. The simulation of the
147 system for a given hydrologic scenario is named as the Base Case.
- 148 • *Use of specific routines for the sequential and iterative use of the previous models to obtain*
149 *the resource costs*. A Modified Case corresponds to the simulation with the same hydrologic
150 scenario and a perturbation by adding (or removing) a differential water volume (Δ Volume) at
151 the location and time of interest. Thereafter, the model reallocates the resource over time and
152 space, using the operating rules, yielding a new economic benefit. The difference in total
153 benefit between the Base and the Modified Case (Δ Benefit) is computed. The ratio
154 Δ Benefit/ Δ Volume is an approximation of the aggregated MROC for the system, and reflects

155 the aggregated economic cost of water scarcity with the existing allocation criteria.
156 Hydro-economic models can be developed “ad hoc” for a specific system or using generic
157 Decision Support System (DSS) tools. AQUATOOL is a generalized DSS for integrated water
158 resources planning and management, including conjunctive use of surface and groundwater.
159 Computer-assisted design modules allow to represent any complex water resource system in a
160 graphical form, giving access to geographically referenced databases and knowledge bases. New
161 modules of the DSS AQUATOOL (Andreu et al., 1996) add tools for the economic assessment of
162 water management in the system (Collazos, 2004; Andreu et al. 2005; Pulido-Velazquez et al.
163 2008). Hydro-economic simulation in DSS AQUATOOL is performed in 2 steps:

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

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

176 **MROC assessment using Economic Optimization**

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

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

200 There is also certain disturbing effect from optimization. The system operation is optimized for
201 long hydrologic times, what means that the optimization is performed with perfect knowledge of
202 future hydrology, what is known as the “perfect foresight” issue (Labadie 1997). The perfect
203 foresight inherent to the deterministic optimization procedure overestimates the efficiency
204 attained, representing an ideal upper bound of what can be achieved with realistic hydrology
205 forecasts (Draper and Lund 2004). Perfect foresight can understate the value of new storage and
206 conveyance capacity and underestimate actual scarcity and scarcity cost (Pulido-Velazquez et al.
207 2004, 2008). But the effects of perfect foresight on the overall performance of the system can be
208 small when improved performance comes predominantly from consistent operation and
209 allocation changes that do not require hydrologic foresight (Newlin et al. 2002).

210 **METHOD AND TOOLS FOR DESIGNING EFFICIENT PRICING POLICIES** 211 **INCLUDING BASINWIDE MROC**

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

219 models at the basin/water resource system scale. The method involves the following steps:

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

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

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

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

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

276 The practical implementation of this method was done with the coordinated use of different
277 modules of the generalized DSS AQUATOOL. The priority-based simulation module, SIMGES,
278 was used to simulate the basinwide effect of the pricing policy on the time series of storage, flow,
279 supply, and deficit of supply. The model applies an optimization algorithm to deal with monthly
280 decisions of water allocation among the different competing uses, minimizing the weighted
281 deviations from the target. The weights are defined consequently with the priorities given to each
282 demand (Andreu et al. 1996). The economic postprocessor, ECOWIN, then uses the operating
283 cost and demand functions to convert the time series of water delivered into net benefits and
284 scarcity costs for each demand and aggregated for the whole system. The storage-dependent step

285 pricing policy is simulated in SIMGES by translating the level of water usage restrictions at each
286 level of price into a coefficient of restrictions to be applied to each target demand depending on
287 the status of reservoir storage at the beginning of each simulation period.

288 **APPLICATION**

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

299 **Priority-based simulation and economic optimization models**

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

312 The non-linear economic optimization model has been implemented using the optimization
313 package GAMS (General Algebraic Modeling System) (Brooke et al. 1998). The economic
314 optimization model (steps 5-6) maximizes the aggregated net benefit from the two demands (or
315 what is the same, minimizing scarcity plus variable operating costs) over the time horizon.
316 Scarcity costs are found by integrating the demand curves from the maximum demand leftward to

317 the delivery. The model involves constraints for the maximum and minimum (dead pool) storage
318 capacity, the minimum environmental instream flow in the last reach of the river, the mass
319 balance equation at the reservoir, and the mass balance at the delivery node.

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

331 **Storage-based step pricing function**

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

350 based pricing functions, the system penalizes water use B and allocates more water to use A (with
351 higher economic values). In this case we obtained lower total net benefits in the pricing policy
352 derived from the economic optimization's averaged MROC.

353 **Optimized storage-dependent step pricing**

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

362 **Step pricing depending on previous inflows**

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

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

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

382
$$p_{\text{year}(t)} = a + b \cdot V_{\text{oct}} + c \cdot Q_{\text{year}(t-1)} + d \cdot (Q_{\text{year}(t-1)} + Q_{\text{year}(t-2)}) \quad (1)$$

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

387 **Seasonal pricing depending on initial storage and previous annual flow**

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

392
$$p_{\text{oct-april}} = a + b \cdot V_{\text{oct}} + c \cdot Q_{\text{apr,year}(t-1)} \quad (2)$$

393
$$p_{\text{apr-sept}} = d + e \cdot V_{\text{apr}} + f \cdot Q_{\text{oct,year}(t-1)} \quad (3)$$

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

397 **Testing price efficiency with synthetic inflow time series**

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

409 **RESULTS AND DISCUSSION**

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

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

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

445 system based on priorities. Finally, multiple synthetic flow time series are used to check how
446 robust the calculation of the expected benefits is.

447 **SUMMARY AND CONCLUSIONS**

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

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

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

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

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

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

517

518 **Acknowledgements**

519 This study has been partially funded by the EU 6th FP project AQUAMONEY (SSPI-022723),
520 the 7th FP GENESIS project (226536), and SAWARES (Plan Nacional I+D+i 2008-2011,
521 CGL2009-13238-C02-01 and C02-02) and SCARCE (Consolider-Ingenio 2010 CSD2009-
522 00065) of the Spanish Ministry of Economy and Competitiveness.

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FIGURE CAPTION LIST

Fig. 1. Scheme of the synthetic case study (DSS Aquatool)

Fig. 2. Monthly inflow into the reservoir

Fig. 3. Economic demand curves.

Fig. 4. Time series of MROC vs. storage for Simulation and Economic Optimization.

Fig. 5. Procedure for deriving the step pricing schedule from the MROC and storage time series

Fig. 6. Storage-based step pricing functions from Priority-based Simulation, Economic Optimization and optimized steps

Fig. 7. Step pricing depending on previous inflows

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 SIMULATION	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