Interactive comment on “Definition of efficient scarcity-based water pricing policies through stochastic programming” by H. Macian-Sorribes et al.

Anonymous Referee #1
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Answers to the Anonymous Referee #1 General Comments

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1. **REVIEW COMMENT**

   I lack a better and more intuitive explanation why the MROC values generated by the SDP need to be post-processed before they can be used as pricing policies. If we assume monthly time steps in the SDP and if the SDP is run to steady state, then MROC will depend on the month of the year, the inflow class (Markov state) and the amount of water in storage. Given stationary climate and static economy, MROC will not change from one year to the next, i.e. users will know prices as dependent on storage and inflow in advance. Line 778/2-3 states “it will be neither operative, nor fair nor secure to implement a pricing scheme in which prices would vary at each time stage”, however if prices should reflect scarcity, they must vary with time, inflow and storage. For instance, in the wholesale power market, prices are highly variable over short time scales. Why is this not feasible for water? This should be motivated and explained in much more detail and requires a major revision and extension of section 2.3.

   AUTHOR’S RESPONSE

   We agree that the pricing policy directly defined by the monthly MROC values obtained in the SDP calculations would be in theory the most efficient one. Although short-term variable pricing might be suitable for hydropower (with operation decisions made in short time intervals, being independent of previous decisions), agriculture would face problems dealing with this pricing policy. Farmers make decisions in annual or inter-annual basis (area to be irrigated, cropping patterns, etc.), being monthly choices dependent on decisions in previous months. They operate as risk-averse investors, as errors in the expectations on crop prices (and cost of other farm inputs) and water deliveries for the year can cause significant economic losses. A pricing policy with a high price variability that would correspond to a certain scarcity conditions would just introduce too much uncertainty in the water price and thus in the sector. Using directly the SDP results will involve 93x12x16 = 17856 MROC (pricing) values. On the other hand, the pricing schemes derived from MROC values were conceived as the basis for a process involving discussion, negotiation and approval of a certain simple pricing policy with certain consensus among the stakeholders. This is why we support the development of an a-priori pricing scheme that establishes the fares to be applied depending on the available storage, so that everybody knows the rule beforehand and can react accordingly. This is why the post-processing of the MROC values driven by SDP was incorporated.

AUTHOR'S CHANGES IN MANUSCRIPT (p 778 / line 1) [additions in underlined italics, eliminations in crossed-out italics]

"*The results given by the SDP algorithm are the optimal allocation policies, benefits and MROC values at each point of the discrete mesh. Those values vary with the month of the year, monthly storages and monthly inflows. A pricing scheme based on those values would be in theory the most efficient. Highly variable prices are normal in hydropower production, in which deregulated electricity markets' prices and demands vary even during the same day and, in consequence, hydropower producers need to make decisions on very short time stages, being independent of previous choices. However, this situation is distinctly different in consumptive demands, especially in irrigated agriculture. The majority of farmers make most of their decisions in annual or inter-annual basis (area to be irrigated, cropping pattern and so on), being monthly choices dependent on decisions in previous months. Farmers act as risk-averse decision-makers, since errors in the expectations of crop prices, input costs and water deliveries can cause significant economic losses. For those reasons, a pricing policy directly based on the monthly MROC values would introduce too much uncertainty in the water price and thus in the agricultural sector.*~~*The time series of MROC values cannot be directly used for the definition of pricing policies: it will be neither operative, nor fair nor secure to implement a pricing scheme in which prices would vary at each time stage. The*~~ *On the other hand, the pricing schemes derived from MROC values were conceived as the basis for a process involving discussion, negotiation and approval of a certain simple pricing policy with certain consensus among the stakeholders. As a result, the* raw MROC values previously obtained have to be post-processed in order to transform them into *simpler a-priori* scarcity-based pricing policies*, so that the rule can be negotiated and known beforehand by everybody, allowing farmers to reach accordingly with a more predictable price.* Several operations must be carried out to transform the time series of MROC into a step pricing policy depending on the system state variables (*t,*St, Qt), in which a step function defines the price to be applied each time period. Those operations can be summarized as: MROC values aggregation/disaggregation, MROC statistical analysis, and step pricing policy construction. *Although the SDP method was used to obtain the MROC time series, the operations explained below can be used regardless of the algorithm employed (another stochastic one such as SDDP, deterministic optimization or simulation) able to provide MROC time series*."

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2. REVIEW COMMENT

The post-processing steps are listed in detail on page 779. It would be good to have a clear, consistent and transparent terminology. For instance, the terms "previous MROC", "combined MROC" and "final MROC" are introduced, but it is not really clear to me what precisely they represent. I am also unclear about the sorting in steps in 6b and 6c. From the SDP, we get a complete set of water values for all discretized storage and inflow states, so why do they have to be sorted? It seems that the aim of the procedure is to "downsample" the SDP results so that prices are constant over larger regions of the state space. As pointed out above, I am not sure I understand the rationale for doing this. At the end of page 779, it is stated that the post-processing must be re-done if performance is "inadequate". It would be good to define adequacy. How much additional cost / foregone benefit would one want to accept in order to keep prices stable?

AUTHOR'S RESPONSE

The "previous MROC" referred to the MROC time series obtained with the SDP; this adjective has been eliminated in the manuscript. The "combined MROC "were the results of the aggregation/disaggregation process performed over the SDP-driven MROC time series; it has been re-named as "aggregated MROC". The "final MROC" term was used to refer to the combined MROC; now we refer to it as "aggregated MROC". Those definitions have been clarified in section 2.3.

With regard to the sorting procedure, it is performed to transform the MROC time series into pricing policies for the reasons given in the answer to comment 1. Furthermore, those operations could be used for any stochastic programming algorithm capable of obtaining MROC time series (e.g. SDDP) as well as deterministic optimization or simulation; while use directly the MROC values obtained with the SDP for the discrete storage and inflow data would make the method suitable only for the SDP, narrowing the potential applicability of the method. A comment about that feature has been added to the end of section 2.3.

The definition of "adequacy" of a pricing policy depends on the case study features, stakeholder preferences and behavior, and management goals (economic efficiency and other constraints and priorities). An easy measure of accuracy is, as suggested in the comment, to put a value on how much money do we bear to lose as a result of using a less complex pricing policy. That value would depend on the user's preferences: an agricultural user might accept lower incomes if the pricing policy maintains prices stable. Alternatively, one can consider a pricing policy as adequate if the benefits obtained by it are close to those achieved by an optimal command-control approach.

AUTHOR'S CHANGES IN MANUSCRIPT (p 778 / line 6) additions in underlined italics, eliminations in crossed-out italics

"Several operations must be carried out to transform the time series of MROC into a step pricing policy depending on the system state variables (*t,*St, Qt), in which a step function defines the price to be applied each time period. Those operations can be summarized as: MROC values aggregation/disaggregation, MROC statistical analysis, and step pricing policy construction. *Although the SDP method was used to obtain the MROC time series, the* *operations explained below can be used regardless of the algorithm employed (another stochastic one such as SDDP, deterministic optimization or simulation) able to provide MROC time series.*

The ~~A~~aggregation/disaggregation of the MROC time series previously obtained is required in order to derive pricing functions at a certain spatial and temporal scale. Regarding the spatial dimension of the intended pricing policy, different pricing schedules for raw water in different zones in the system will better capture the MROC spatial variability. However, the complexity of pricing policies will probably imply greater implementation difficulties. With regard~~s~~ to the temporal scale, *as stated earlier*, pricing policies varying at a lower time resolution (seasonal or monthly) are more accurate than annual ones, although they might also face more implementation problems and higher uncertainty in future prices. Defining a general procedure to aggregate/disaggregate MROC ~~values~~ *time series* is difficult, since it depends on the desired pricing policy features and each system unique features. An example of aggregation/disaggregation process for the specific features of the desired pricing policy is shown in the case study section.

Once the ~~combined~~ *aggregated* MROC values are obtained, their cumulative probability distribution can be determined. Several characteristic ~~MROC~~ values can then be chosen using different percentiles of the cumulative probability distribution. Those characteristic values can be used to estimate the MROC- state relationship by: *1)* sorting the time series of state variables obtained with SDP according to their respective *aggregated* MROC values; *2)* selecting the MROC-state pairs in which the MROC value was a characteristic one; and *3)* organizing the results in the form of state-MROC steps. To sum up, the method presented in this paper can be divided in the following steps:

1. Definition of the main pricing policy features
2. Development of a hydro-economic stochastic programming model of the system
3. Determination of MROC (marginal water values or λ-values) time series at the reference nodes (e.g. main reservoirs)
4. Aggregation/disaggregation of ~~previous~~ MROC time series to calculate the ~~combined~~ *aggregated* MROC *values*
5. Development of a statistical analysis over the ~~final~~ *aggregated* MROC ~~time series~~*values* to obtain their cumulative probability distribution
6. Building of k steps by:
    a. Choose k different cumulative probability ~~MROC~~ values (characteristic values)
    b. Sort according to the *aggregated* MROC values the system state values obtained in the stochastic programming run
    c. Obtain, for each characteristic ~~MROC~~ value, the system states associated to it
    d. Summarize all the possible state values associated to each ~~MROC~~ *characteristic* value in the form of steps
7. Definition of several step pricing policies based on the obtained steps

Pricing policies can be simulated to assess their performance and to compare them to ~~SDP-derived policies~~ *the SDP results and to other alternatives such as different operating rules*. In case the pricing policies' performance is found to be inadequate, the process must be restarted: the pricing policies' features are reassessed and the build-up and analysis stages must be redone. *The most straightforward way to determine its adequacy is to quantify the forgone benefits that the users would be willing to accept as counterpart of using a simpler pricing policy. It is impossible to establish a unique threshold value since it totally depends on the system features. An alternative approach, employed in the case study of this paper, is to compare the performance of the pricing policy with the one achieved by the optimal operating rules expressed by the SDP results. In that way, a pricing policy could be considered as adequate as long as it obtains similar economic returns than those for the optimal policy.*"

3. REVIEW COMMENT

P. 782: It seems that the objective in the case study was to obtain a pricing policy that would only depend on the combined storage of both reservoirs. Wouldn't it be a logical thing to then also design the SDP with one combined storage only? It also became clear from Fig 7 that the objective in the case study was to obtain a pricing policy that only depends on storage but not on the month of the year. Intuitively, one would expect that the water value must change in time. Having an empty reservoir at the beginning of the rainy season is much less critical than at the beginning of the dry season... Or are these reservoirs so small that they can anyway not be used for seasonal storage (does **not seem to be the case from the info given in table 1)?**

AUTHOR'S RESPONSE

The storage combination was not done because of the particular features of the system. Aggregating the storage would allow to consider neither the seepage losses at Sichar reservoir nor the fact that the intake for the C220 irrigation district is located upstream the Sichar reservoir. In addition, unifying the reservoirs would make impossible to test pricing policies in which storages were considered separately, in case the simpler ones were found not to be adequate.

According to the features of the case study (only agricultural users with mainly orange orchards, steady annual inflows, existence of a previous operating rule and so on) it appears that a pricing policy as simpler as the ones tested would have the best change to be implemented in real life. Rather than an objective, it seemed to us as the best pricing policy to test at first (it is the simplest possible one). The test was successful (we obtained the same benefits as the SDP-derived operating rules) so we did not try more complex pricing policies. A comment about it has been added to the section 3.3.

Water values do change in time as well as in space, but as explained in the answer to comment 1, there are circumstances in which it is worth to sacrifice the ability of the pricing policy to reflect the water values in order to reduce the price variability and uncertainty, making easier the decision-making process that users must carry out.

The reservoirs in the Mijares river are used for seasonal storage, storing water during winter to use it on summer. If their levels are higher enough, then they can work as inter-annual facilities. This behavior can be observed in figure 5, in which both intra and inter-annual patterns can be found. It is true that having empty reservoirs at the beginning of summer is critical while the same situation at the beginning of autumn is not. However, the probabilities of those events are not the same, since the latter phenomenon is less frequent. This behavior can be seen in Fig. 5, in which a refill cycle of at least 20 Mm^3 is noticed every year. Due to that cycle, even if the pricing policy does not vary across time, it has an internal time distribution: most of the higher MROC values that formed the price for low storage levels were found at the beginning of the refill season, while low MROC values associated to higher storage levels were found at the start of the drawdown season. Due to that, even with the same pricing policy, water prices are able to reflect in some way water scarcity. That is the reason why in this case study a simple pricing policy is able to achieve the same economic performance than a complex optimal policy. Furthermore, that is the reason why the best pricing policies for the whole period are not adequate during droughts: in drought situations the in-year pattern of the water values is modified, meaning that pricing policies with different patterns (non-drought ones) are not capable of reproducing the drought-specific MROC distribution in a very dry year. An explanation of the in-year features of those pricing policies is given in section 4.

AUTHOR'S CHANGES IN MANUSCRIPT

(p 783 / line 18) additions in underlined italics, eliminations in crossed-out italics
"Regarding Table 2 and Fig. 8a, only slight differences can be found between policies. All pricing policies increase the economic results of current management policies by around EUR 0.70 million per year, being ~~*close*~~ *similar* to the ones obtained with the direct use of the SDP policies. *For that reason, we consider those pricing policies to be adequate, being not necessary to test complex ones*. This situation is caused by the natural robustness of the Mijares river water system and by the homogeneity of the cropping pattern (mainly citrus crops, mostly oranges) found in the basin."

(p 784 / line 17) additions in underlined italics, eliminations in crossed-out italics
"This paper presents a method to design an efficient scarcity-based pricing policy based on marginal water values (MROC) derived from stochastic programming. The method is applied to a case study, the Mijares river basin, in Spain. The results show that the benefits from the application of the resulting pricing policies are close to those obtained by the optimal SDP policy for both the entire historical hydrological data series and the drought conditions. By pricing marginal water opportunity costs, water would be reallocated to the highest-valued uses, significantly increasing the total net benefit of water use in the basin (by EUR 0.75 million per year).
The reason why a simple pricing policy is able to achieve similar performance than a complex optimal operating rule in this case study is due to the in-year time pattern possessed by this policy: the majority of the MROC values that determined the water prices for the lower storage levels correspond to start-of-refill ones, while the MROC values associated to high storage levels are start-of-drawdown ones. For that, the prices triggered vary across time in accordance to the refill-drawdown cycle of the system, reproducing in some way the water value annual cycle."

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4. REVIEW COMMENT

Water values or MROC depend on the inputs used in the hydroeconomic model. Some of these inputs (e.g. demand curves, return flow fractions etc.) are highly uncertain. It would be good to include an analysis how the uncertainties in model inputs translate into uncertainties in MROC and thus in the pricing policies, and how such uncertainties would impact on the performance of the pricing policy.

AUTHOR'S RESPONSE

Apart from the demand curves, the inputs concerning the Mijares River basin, such as evaporation and seepage losses, were based on decades of recorded data, experience and calibration, reaching a good fit to the observed values, as reported in some of the references of the manuscript such as Andreu et al (1987), Alvarez-Mendiola (2012) and CHJ (2009). One of the reasons behind our case study decision was precisely the amount of reliable data. With respect to return flows, they do not go back to the river, because either there are not surface returns or there are other small users not included in the model that employ those return flows.

The most important source of uncertainty is the demand curves, since they directly affect the MROC values. Given the strong influence of the demand curves in the results, demand curves should be properly estimated and tested. The problem we found is that, given that demand curves are complex and non-linear, performing a sensitivity analysis is difficult and entirely dependent on the way the curves are modified. Moreover, since there are several different demand curves affecting the performance of the system, we found that a sensitivity analysis capable of capturing this diversity was beyond the scope of this manuscript. Future research activities will address this issue using a hybrid optimization-simulation approach in order to be computationally tractable.

The author's changes in manuscript regarding this comment have been done in conjunction with the 2nd referee general comment 2.

AUTHOR'S CHANGES IN MANUSCRIPT (p 784 / line 17, right after the changes made regarding the previous comment) additions in underlined italics, eliminations in crossed-out italics

"*Taking into account the uncertainties associated to the inputs of the model, the predictions concerning the pricing policy performance are therefore uncertain. The most important source of uncertainty is the demand curves, since they directly affect the MROC values and the reliability of the simulated performance of a pricing policy. Given the strong influence of the demand curves in the results, demand curves should be properly estimated and tested.*"

Answers to the Anonymous Referee #1 Detail Comments

1. **REVIEW COMMENT**
   772/4: Maybe "scarcity-dependent" is better than "scarcity-based"

   AUTHOR'S RESPONSE
   Although both could be applied in the context of the manuscript with a very similar meaning, we found scarcity-based a much more common term in the economic literature rather than scarcity-dependent.

   AUTHOR'S CHANGES IN MANUSCRIPT additions in underlined italics, eliminations in crossed-out italics
   No changes were made

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2. **REVIEW COMMENT**
   772/15: "on" should be "in"

   AUTHOR'S RESPONSE
   "On" has been replaced by "in"

   AUTHOR'S CHANGES IN MANUSCRIPT (p 772 / line 15) additions in underlined italics, eliminations in crossed-out italics
   "One of the main challenges in integrated water resources management (IWRM) is…"

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3. **REVIEW COMMENT**
   772/17: This may be a bit of a Euro-centric view. In China and parts of Africa (e.g. Ethiopia), new hydraulic infrastructure is built at an unprecedented scale. . .

   AUTHOR'S RESPONSE
   A clarification was added in the manuscript

   AUTHOR'S CHANGES IN MANUSCRIPT (P772 / L16-17) additions in underlined italics, eliminations in crossed-out italics
   "Given that in the majority of the developed world the building of new water supply systems has well-passed its zenith, water management…"

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4. **REVIEW COMMENT**
   774/4: delete "the" before "economic theory"

   AUTHOR'S RESPONSE
   The word "the" was eliminated

   AUTHOR'S CHANGES IN MANUSCRIPT (p 774 / line 4) additions in underlined italics, eliminations in crossed-out italics
   "A pricing policy is efficient, according to ~~the~~ economic theory, if the prices charged…"

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5. **REVIEW COMMENT**

   780/13: "not" should be "no"

   AUTHOR'S RESPONSE

   The word "not" was replaced by "no"

   AUTHOR'S CHANGES IN MANUSCRIPT (p 780 / line 13) additions in underlined italics, eliminations in crossed-out italics

   "explicitly represented in the optimization model, as there is no hydraulic connection…"

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6. **REVIEW COMMENT**

   782/24 ff: Why not also compare to the full set of MROCs as generated by the SDP? I guess you do it and call it "SDP" in fig 8, but it is in effect also a pricing policy. . .

   AUTHOR'S RESPONSE

   The "SDP" alternative corresponds to the policies obtained by the SDP algorithm, once interpolated as in Tejada-Guibert et al (1993). Those policies were analyzed using the same simulation model as the current operating rules and the pricing policies. They do not reflect a pricing policy, but the solution based on the optimal rules from the SDP. Although the comparison suggested by the reviewer would certainly be useful, it is beyond the scope of our paper, which is presenting one new method and make a comparative analysis between its performance and the one offered by operating policies defined using traditional ways. This comparison would be require additional research to be addressed in further studies.

   AUTHOR'S CHANGES IN MANUSCRIPT

   (p 783 / line 16) additions in underlined italics, eliminations in crossed-out italics

   "Figure 8a shows the time series of benefits resulting from SDP*-derived policies (the optimal policies obtained from the SDP once interpolated as suggested by Tejada-Guibet in 1993)*, current management rules and the best pricing policies for the 1940–2009 period."

   (p 786 / line 12) (right before the acknowledgements section) additions in underlined italics, eliminations in crossed-out italics

   "*Further lines of research that could be addressed would include analyzing the impact of the uncertainties found in the model, as well as well as comparing the pricing policies defined in this paper with ones defined after the methodology developed in Pulido-Velazquez et al (2013) or using other possible approaches.*"

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7. **REVIEW COMMENT**

   783/6: Why not use the same model as used for the SDP runs? Does the MATLAB model include more spatial/economic detail than the SDP scheme?

   AUTHOR'S RESPONSE

   Both models represent the system in the same detail and possess the same features. The change of programming language between the SDP and the simulation models did not regard to any technical issue, it was just to take advantage of previous works. A comment about that was added to the paper.

AUTHOR'S CHANGES IN MANUSCRIPT (p 783 / line 5) additions in underlined italics, eliminations in crossed-out italics

"Each pricing policy was simulated for the 1940–2009 period with a hydro-economic simulation model, previously built using MatLab (Macian-Sorribes, 2012) whose features are identical to the SDP one."

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8. REVIEW COMMENT

783/last paragraph: One may conclude that the case study is not really well suited to demonstrate the methodology described in the paper, if differences in the performance of the various pricing policies are so small.

AUTHOR'S RESPONSE

We agree that other case studies would have likely shown greater differences due to the features possessed by the Mijares river, outlined in section 2.4. We choose that case study since it is one of the most documented rivers in Spain and, in consequence, we could built a model close to reality without the need of additional studies, for both the physical and the economic features. On the other hand, the fact that several pricing policies achieved an economic performance close to optimal operating rules is an advantage of the case study in the sense that it proves that this methodology is able to obtain pricing policies whose performance is optimal. Furthermore, the existence of several pricing policies with the same global benefits but different benefits for each user proves that the methodology is flexible enough to let the decision-maker distribute the costs and benefits between the different users. Therefore, the case study election was bad in certain aspects, but good in others.

AUTHOR'S CHANGES IN MANUSCRIPT (p 783 / line 28) additions in underlined italics, eliminations in crossed-out italics

"As the income losses are non-linear with respect to the deliveries, that deficit distribution improves the total economic return for the system. *Despite having the same global benefits, the way they are distributed among the users changes for all the pricing policies tested, being necessary to take it into account when deciding which one to be implemented.*"

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9. REVIEW COMMENT

783/24: "relocations" should probably be "reallocations"

AUTHOR'S RESPONSE

"Relocations" has been replaced by "reallocations".

AUTHOR'S CHANGES IN MANUSCRIPT (p 783 / line 24) additions in underlined italics, eliminations in crossed-out italics

"The benefit improvement caused by pricing policies is due to temporal re*al*locations:"

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10. REVIEW COMMENT

784/23-25: I do not understand this statement.

AUTHOR'S RESPONSE

In previous works, trial-and-error processes were required to adjust the pricing policies' performance, since the method adopted was not able to provide optimal economic returns: prices were systematically modified and the model was run again to determine if they were adequate or not. The procedure developed in this paper, on the other hand, did not require any random modification, since all the pricing policies were product of combining the MROC intervals in the way exposed in the paper. However, in accordance to the 2nd referee general comment 1, the avoidance of trial-and-error processes has not been considered as an important difference in comparison with the modifications introduced by this methodology. Consequently, the statement has been eliminated.

The author's changes in manuscript due to this comment have jointly with the 2nd referee general comment 1.

AUTHOR'S CHANGES IN MANUSCRIPT (p 784 / line 17) additions in underlined italics, eliminations in crossed-out italics

"~~The differences between this~~*Unlike the* method ~~and the one~~ proposed in Pulido-Velazquez et al. (2013)*, this one uses* ~~consist basically of: (1) using~~ a stochastic programming approach instead ~~a~~ *of* deterministic programming or ~~a~~ simulation ~~one; and (2) obtaining pricing policies via statistical analysis and system state sorting according to the MROC values. The use of stochastic programming methodologies implies that the MROC-state relationship obtained reflects an optimal but realistic situation, instead of a non- optimal situation (simulation) or an unrealistic optimal one (deterministic optimization). In addition, the method proposed in this paper to obtain pricing policies avoids trial-and-error procedures, whose time requirements are hard to estimate~~. *It also employs a different method to derive the pricing policies based on the MROC and state time series.*"

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11. REVIEW COMMENT

785/Bullet 3: Does this mean that pricing policies change in time after all (drought/no drought)?

AUTHOR'S RESPONSE

In each pricing policy run the same pricing policy was used for the whole period, they were no pricing policy changes. The fact is that the pricing policies with the best performance for the whole period (1940-2009) were different from the best ones when looking at the drought period (1977-1986). In theory, pricing policies could be defined differently for normal situations and drought periods. But since we are dealing here with a-priori pricing rules, this would require a mechanism that could forecast the droughts. This is why in this case we define a pricing policy that is applied to the whole period.

The reference to the droughts issue has been removed from the text.

AUTHOR’S CHANGES IN MANUSCRIPT (p 785 / bullet3) additions in underlined italics, eliminations in crossed-out italics

“~~*.It can be used to define pricing policies either under general conditions or drought events*~~”

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12. REVIEW COMMENT

785/786: Bullet 4 is not clear. An example may help.

AUTHOR’S RESPONSE

Bullet 4 means that the desires of the users/stakeholders about the pricing policy features can affect the aggregation/disaggregation mechanism. An example has been added to the text. Therefore, it is crucial to know those desired features via participatory processes.

AUTHOR’S CHANGES IN MANUSCRIPT additions in underlined italics, eliminations in crossed-out italics

“~~*4*~~*3*. Participatory framework processes ~~*are needed*~~ *might be desirable* to define the features and characteristics that the ~~*desired*~~ pricing policies should have, ~~*as they condition the MROC aggregation/disaggregation mechanism*~~*in order to find as much consensus as possible for its implementation*. ~~*These procedures are key milestones for the pricing policy implementation.*~~”

Interactive comment on “Definition of efficient scarcity-based water pricing policies through stochastic programming” by H. Macian-Sorribes et al.

Anonymous Referee #2
Received and published: 24 April 2015

Answers to the Anonymous Referee #2 General Comments

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1. **REVIEW COMMENT**
   The authors have published several related papers in this area in recent years, and it is not entirely clear to me how they are distinguishing this work from their earlier work. I understand that previous papers, or at least Pulido-Velazquez et al. 2013, used an assumption of perfect hydrologic foresight, which certainly represents a limitation, but is the elimination of this assumption the primary difference between that paper and this one? Please elaborate.

   AUTHOR’S RESPONSE
   The new approach uses a stochastic programming procedure instead of a simulation or a deterministic optimization. Previous works relied on simulation or deterministic optimization to design the *a priori* pricing policies, both of them subjected to imperfections that hinder its optimality. We considered stochastic optimization as the best procedure to define an optimal pricing policy, since deterministic optimization is hindered by the perfect foreknowledge of future inflows (which is an unrealistic assumption that makes its results unattainable in real life) while simulation does not offer optimal results (as its goal is to follow certain a priori operating rules that can be non-optimal). Furthermore, we propose a different approach for deriving the a priori pricing function based on the MROC-state time series.
   The author’s changes in manuscript due to this comment have been made jointly with the 1st referee detail comment 10.

AUTHOR'S CHANGES IN MANUSCRIPT (p 784 / line 17) additions in underlined italics, eliminations in crossed-out italics

"~~*The differences between this*~~*Unlike the* method ~~*and the one*~~ proposed in Pulido-Velazquez et al. (2013)*, this one uses* ~~*consist basically of: (1) using*~~ a stochastic programming approach instead ~~*a*~~ *of* deterministic programming or ~~*a*~~ simulation ~~one; and (2) obtaining pricing policies via statistical analysis and system state sorting according to the MROC values. The use of stochastic programming methodologies implies that the MROC-state relationship obtained reflects an optimal but realistic situation, instead of a non- optimal situation (simulation) or an unrealistic optimal one (deterministic optimization). In addition, the method proposed in this paper to obtain pricing policies avoids trial-and-error procedures, whose time requirements are hard to estimate~~. *It also employs a different method to derive the pricing policies based on the MROC and state time series.*"

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2. **REVIEW COMMENT**

While I understand the idea of marginal cost pricing in theory, I have many questions regarding how it would be implemented in practice. Estimates of marginal (or market) prices are notoriously poor in many contexts, and the same is likely to be the case here, so how does the system respond to a poor estimate? If prices are set too low and demand outstrips supply, what happens? Is there a cap on supply, and if so, how and on whom is it enforced? If prices are set too high, there is no physical limitation, but there could be significant economic losses. Given that most of the demand is agricultural, and therefore likely to be very elastic, it would seem that small errors in the estimated prices could give rise to very large discrepancies between the amounts of water demanded (at the MROC) and those estimated. How would this be managed?

AUTHOR'S RESPONSE

We agree this is a key issue. The response of the system to a wrong price estimate would be an unbalance between resources and demands; this unbalance already happens with the current management of the system during water scarcity periods, in which demand surpasses supply. If this occurs in the implementation of the measures, the pricing policy would need to be corrected (in an adaptive approach). Actually, we conceive this pricing policy as a first preliminary estimate of an efficient policy, to be further refined, discussed and negotiated.

If the demand outstrips the supply, then water could be restricted according to certain priorities now established by law or other procedure to be defined in advance.

Financial compensations could be paid in case that pricing policies are set too high. In fact, part of the revenues generated by the pricing policy could be used to increase the accuracy of the demand curves and thus of the pricing policies, as well as to invest in increasing water security and deal with potential equity issues. An explanation about that has been added to section 4.

The accuracy in the estimated demand curves is certainly important in the reliability of the simulated performance of a pricing policy. We found that agricultural demand curves have often both elastic and inelastic reaches, which vary across the price interval, with lower discrepancies in more inelastic parts. In any case, given the strong influence of the demand

curves in the results, demand curves should be properly estimated and tested.
The author's changes in manuscript due to this comment have been made jointly with the 1st referee general comment 4.

AUTHOR'S CHANGES IN MANUSCRIPT (p 784 / line 17) additions in underlined italics, eliminations in crossed-out italics
"*Given the uncertainties associated to the inputs of the model, the predictions concerning the pricing policy performance are uncertain. The most important source of uncertainty is the demand curves, since they directly affect the MROC values and the reliability of the simulated performance of a pricing policy. Given the strong influence of the demand curves in the results, demand curves should be properly estimated and tested.*
If water prices are poorly estimated, the result will be an unbalance between resources and demands: this unbalance already happens with the current management of the system during water scarcity periods, in which demand surpasses supply. In that case, the pricing policy should be corrected in an adaptive approach. In cases demand overtook supply due to price being lower than required, water supplies would need to be curtailed according to certain priorities determined either by negotiation or by law, in order to rematch demand and supply. On the other hand, if prices are set too high, financial compensations should be paid to the affected users. In order to avoid those situations, part of the revenues generated by the pricing policy should be employed to increase the accuracy of the estimated demand curves. Furthermore, they may be invested in water security increase or deal with equity issues."

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3. **REVIEW COMMENT**
Along similar lines, one of the largest obstacles to implementing some form of water market is the concern over high prices that would limit some activities' (i.e. agricultural) consumption of water. In order for this MROC pricing approach to be used, the obstacle of rising prices would have already been overcome, yet there would still be huge information requirements on the part of the administering water agency if it were going to accurately estimate the MROC month-after-month and year-after-year. Given that concerns over higher prices would have been overcome, why not just implement a market instead of the MROC pricing approach, it would certainly be more efficient given that the users would make decisions based on their own valuations, and probably easier to administer? I would like to better understand the circumstances under which the authors' feel that the MROC approach is preferable to a market, as these are not clear to me.

AUTHOR'S RESPONSE
Water market will be certainly another approach to enhance economic efficiency in water allocation in the system. In Spain, formal (spot) water markets are allowed by law since 1999, but in practice, only in a few occasions they have been implemented, and never in this system. Factors like high transaction costs, farmers' reluctance to participate, low physical connectivity, etc., often prevent more transfers. While the experience and literature on water markets is more abundant, water pricing is one of the most underused tools for dealing with water scarcity relative to its potential. Despite its limitations,

drawbacks and barriers and issues for its implementation, water pricing offers some interesting features: contributes to match supply and demand, generates revenues for the administration (which could be then invested in increasing water supply security, or as a potential rebate to compensate economic losses for dealing with equity issues), and maintain customer choices (against command-and control policies). On the other hand, the river basin authority holds the formal control of the system, what I essential for addressing environmental requirements, third party effects, and so on.

AUTHOR'S CHANGES IN MANUSCRIPT (p 785 / line 4) additions in underlined italics, eliminations in crossed-out italics

"*Comparing pricing policies with water markets, both will be theoretically valid approaches for enhancing economic efficiency in water allocation in the system. In Spain, formal (spot) water markets are allowed by law since 1999; but in practice, only in a few occasions have them been operative, and never in this system (Palomo-Hierro et al., 2015). Factors like high transaction costs, farmers' reluctance to participate, low physical connectivity, etc., often prevent more transfers. While the experience and literature on water markets is more abundant, water pricing is clearly underused regarding its potential for dealing with water scarcity. Despite its limitations, drawbacks, barriers and issues for its implementation, water pricing offers some interesting features: contributes to match supply and demand, generates revenues, and maintain customer choices (against command-and control policies). On the other hand, the river basin authority holds the formal control of the system, what is essential for addressing environmental requirements, third party effects, and so on.*
~~*To gain social acceptability and policy equity, mechanisms of financial compensation can be implemented (e.g., Tilmant et al., 2009). Additional financial resources generated could be them be employed to compensate the users, or to develop adequate infrastructure to increase water security (for example, by financing desalination plant that reduce water scarcity). The main objective in the design of the pricing policies discussed here focuses on the use of water prices as economic instrument for an efficient management of the interaction between supply and demand. The role of pricing for cost-recovery of water services (pricing as financial instruments) will require a complementary analysis.*~~"

Answers to the Anonymous Referee #2 Detail Comments

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1. **REVIEW COMMENT**
   I **think that the orientation of the reservoirs in Figure 3 may be incorrect. Aren't the wide ends of the reservoir symbols supposed to be at the downstream side and the narrow ends at the upstream side?**

AUTHOR'S RESPONSE

Both configurations are possible and often employed in different Decision Support Systems (DSS) for water resources management: one could be the reservoir viewed from the top, and the other, a top view of the dam shape. The reservoir orientation adopted in this paper correspond to the one employed by the AQUATOOL DSS shell, while others like MODSIM employ the configuration suggested by the reviewer.

AUTHOR'S CHANGES IN MANUSCRIPT additions in underlined italics, eliminations in crossed-out italics

No changes were made.

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2. **REVIEW COMMENT**

   pg 785, line 6 has several typos

   AUTHOR'S RESPONSE

   The typos were corrected. However, the sentence in which they were found has been eliminated in response to other comments.

   AUTHOR'S CHANGES IN MANUSCRIPT (p 785 / line 5) additions in underlined italics, eliminations in crossed-out italics

   "~~Additional financial resources generated could be them be employed to compensate the users, or to develop adequate infrastructure to increase water security (for example, by financing desalination plant that reduce water scarcity).~~"

(5)

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Definition of efficient scarcity-based water pricing policies through stochastic programming

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Abstract

Finding ways to improve the efficiency in water usage is one of the most important challenges in integrated water resources management. One of the most promising solutions is the use of scarcity-based pricing policies. This contribution presents a procedure to design efficient pricing policies based on the opportunity cost of water at the basin scale. Time series of the marginal value of water are obtained using a stochastic hydro-economic model. Those series are then post-processed to define step pricing policies, which depend on the state of the system at each time step. The case study of the Mijares river basin system (Spain) is used to illustrate the method. The results show that the application of scarcity-based pricing policies increases the economic efficiency of water use in the basin, allocating water to the highest-value uses and generating an incentive for water conservation during the scarcity periods. The resulting benefits are close to those obtained with the economically optimal decisions.

1 Introduction

One of the main challenges ~~on~~ in integrated water resources management (IWRM) is improving the efficiency in water usage while balancing it with equity. Given that ~~the~~ in the majority of the developed world the building of new water supply systems has well-passed its zenith, water management strategies are now devoted to achieve better operating policies. Several criteria can be considered when designing a policy for water allocation: flexibility in the allocation, security of tenure for the users, real cost recovery, predictability of its performance, fairness and acceptability (Dinar et al., 2007). Each system has a unique configuration and, in consequence, a unique combination of factors that lead to an adequate management policy.

There are four major water allocation mechanisms: public water allocation, water markets, user-based allocation and marginal cost pricing. Public water allocation provides an adequate treatment of water as a public good, allows the development of large-scale infrastructures often beyond the private investment capacity, and focuses on equity issues and non-economic objectives. However, it usually fails in achieving optimal economic performance, leads to water prices which are below the water value, and provides no incentive to water saving and efficient use (Meinzen-Dick and Mendoza, 1996). Water markets encourage both sellers and buyers to use it efficiently, provide flexible allocation mechanisms and allow considering the real value of the employed resource. On the contrary, unique characteristics of water can turn markets into a bad allocation mechanism if externalities are not adequately considered (Garrick et al., 2009). User-based allocation, in which water users regulate water resources by themselves, is especially suited for local needs in water management, and is likely to be accepted by the users. However, it may be inadequate in inter-sectorial allocation, requiring also a very transparent structure (Dinar et al., 2007).

Finally, marginal cost pricing provides a theoretically adequate way to consider water values in allocation, encourages users to save it and puts water in its most valuable uses, leading to efficient allocations. It also can play a major role in the long run planning and conservation of water supplies, delaying the need of capacity expansions and offering higher economic returns while holding rationing requirements (Gysi and Loucks, 1971). However, marginal cost pricing would require estimating the non-accounting opportunity costs involved in water allocation (Griffin, 2001). Calculating the marginal value of water is challenging as it varies in space and time according to supply-demand imbalances; requires adequate monitoring; and has some difficulties to deal with equity when water prices are beyond what lower-value users can afford (Dinar et al., 2007). Moreover, administrative constraints on price charges can limit their benefits (Dandy et al., 1984). In Europe, the EU Water Framework Directive (European Commission, 2000) calls for the implementation of new pricing policies that assure the contribution of water users to the recovery of the cost of water services (financial instrument) while providing adequate incentives for an efficient use of water (economic instrument). Not only financial costs should be recovered, but also environmental and resource (opportunity) costs. This issue has been addressed through the use of hydro-economic models as tools able to couple physical and economic water resource aspects (Heinz et al., 2007; Pulido-Velazquez et al., 2008, 2013; Riegels et al., 2013; Ward and Pulido-Velazquez, 2008).

A pricing policy is efficient, according to ~~the~~ economic theory, if the prices charged correspond to the marginal cost of water. Therefore, it must take into account supply costs, opportunity costs and externalities (Rogers et al., 2002). Measuring the opportunity costs of scarce water is difficult: since water markets are usually absent or ineffective, scarcity values are not reflected in the water prices. Given that opportunity cost depends on the alternative uses, an integrated basinwide approach is needed to simultaneously account for all major competing water uses in the basin (Rogers et al., 2002; Pulido-Velazquez et al., 2013). The assessment of these opportunity costs requires a systems approach and a proper method to estimate the value of water across the different users (Young, 2005; Pulido-Velazquez et al., 2008). If pricing policies reflect the entire basinwide marginal opportunity costs, then they will act as an economic instrument for efficient water resources management, modifying the demand-supply interaction by acting on the demand side and supporting water allocation to the most valuable users.

The Marginal Resource Opportunity Cost (MROC), or marginal value of water, can be defined as the benefits that would have been obtained at one location and one time if the available resource at that location and time had been increased by one unit (Pulido-Velazquez et al. and 2013; Tilmant et al., 2008, 2014). MROC can be derived from hydro-economic models. Pulido-Velazquez et al. (2013) developed a method to obtain scarcity-based pricing policies using MROC values, in which the time series of MROC obtained after running a hydro-economic model are post-processed to derive step pricing policies whose performance can be simulated using a Decision Support System (DSS) shell. However, in those studies pricing policies were based on either priority-based simulation (which are not representing an optimal policy) or deterministic hydro-economic optimization, with the inherent limitation of the perfect foresight (the optimization algorithm knows future flows in advance and, in consequence, it has an unrealistic advantage that diminish the applicability of the results) (Labadie, 2004).

The main purpose of this paper is to propose a method for the design of scarcity-based water pricing policies based on the MROC derived from a stochastic hydro-economic model. With stochastic programming procedures, uncertainty is taken into account in the optimization process. Therefore, it removes the effect that the "perfect foresight" phenomenon causes in the marginal values, which are flattened across time losing an important part of their short-term variability. The marginal values obtained using stochastic programming are representative of an optimal policy while reflecting the future uncertainties in the system's inflows. After describing the method to obtain the MROC values, we propose a method for the definition of a stochastic-programming-based water pricing policy. Finally, a case study is developed to prove and illustrate the methodology using a hydro-economic simulation model of the Mijares river basin system (Spain). Pricing policies are applied in this paper exclusively as economic instruments whose purpose is achieving an efficient use of water. Financial issues are not addressed.

2 Method and materials

2.1 Assessment of the Marginal Resource Opportunity Cost (MROC)

For a specific water demand, the benefit obtained by the user, B_i, given a change in water delivery level from x_1 to x_2 can be calculated by integrating the demand curve (D_i) (Fig. 1):

$$B_i = \int_{x_1}^{x_2} D_i(q)\mathrm{d}q \tag{1}$$

Similarly, for a given location L and time t, the benefit B_t achieved by a change in its state $s_{L,t}$ (water availability) from x_1 to x_2 can be calculated integrating the marginal water value (or MROC) function:

$$B_t = \int_{x_1}^{x_2} \mathrm{MROC}_{L,t}(s_{L,t})\mathrm{d}s \tag{2}$$

The MROC can be defined as the derivative of the benefit function with respect to the system state. Therefore, if the MROC integration obtains the systemwide benefits, the MROC can be calculated as:

$$\mathrm{MROC}_{L,t} = \frac{\mathrm{d}B_t(s_{L,t})}{\mathrm{d}s} \tag{3}$$

The MROC value for a specific location and time can be estimated: (1) under a simulation approach, as the benefits obtained by an increase of one unit in the available resource at that location and time (Pulido-Velazquez et al., 2008, 2013); and (2) under an optimization approach, as the shadow value, dual variable or Lagrange multiplier associated to the mass-balance equation at the desired place and the specified time (Pulido-Velazquez et al., 2008, 2013; Tilmant et al., 2008).

2.2 MROC assessment through stochastic programming

Stochastic programming (SP) procedures are powerful and useful methodologies to derive optimal management of water systems with uncertain inputs (Tejada-Guibert et al., 1993). Various SP algorithms are available. Among them, Stochastic Dynamic Programming (SDP) has been widely used in water resources management because: (1) it is able to handle non-linearities in the objective function in an efficient way; (2) the inflow uncertainty representation is clear and simple; and (3) it treats the decision-making process sequentially, as done in real-life operation (Labadie, 2004). The SDP algorithm solves the Bellman's recursive equation as follows:

$$F_t(\boldsymbol{S}_t, \boldsymbol{Q}_t) = \max_{D_t}\left[B_t(\boldsymbol{S}_t, \boldsymbol{Q}_t, D_t) + E_{\boldsymbol{Q}_{t+1}|\boldsymbol{Q}_t}\{F_{t+1}(\boldsymbol{S}_{t+1}, \boldsymbol{Q}_{t+1})\}\right] \tag{4}$$

~~where~~ Where F_t is the total benefit function; $\boldsymbol{S}_t$ the current (time t) system state vector; $\boldsymbol{Q}_t$ current inflow vector; D_t decision made at time step t; B_t immediate benefit function; $E_{\boldsymbol{Q}_{t+1}|\boldsymbol{Q}_t}$ expectation operator between the current and future inflows; and F_{t+1} future benefit function or benefit-to-go function.

In the SDP method, the state variables $\boldsymbol{S}_t$ and $\boldsymbol{Q}_t$ are discretized over all the state space forming a grid, allowing only transitions between grid points. The expectation operator is then defined by using a Markov chain that relates the current hydrological state $\boldsymbol{Q}_t$ with all the possible future states $\boldsymbol{Q}_{t+1}$ through a set of transition probabilities.

With the application of the previously showed equation, the optimal policies $D_t(\boldsymbol{S}_t, \boldsymbol{Q}_t)$, and benefit-to-go function $F_t(\boldsymbol{S}_t, \boldsymbol{Q}_t)$ are calculated at the grid points. Then, interpolation methodologies can be applied to obtain the optimal policies $D_t^*(\boldsymbol{S}_t, \boldsymbol{Q}_t)$ and the optimal benefits $F_t^*(\boldsymbol{S}_t, \boldsymbol{Q}_t)$ over the entire state-space. An alternative is to use a reoptimization approach as in Tejada-Guibert et al. (1993). With this approach, the Bellman function is implemented forward with the SDP-derived benefit-to-go functions as inputs.

$$F_t(\boldsymbol{S}_t, \boldsymbol{Q}_t) = \max_{D_t} \left[B_t(\boldsymbol{S}_t, \boldsymbol{Q}_t, D_t) + \sum_q \left\{ p_{p,q}^t \cdot F_{t+1}^*(\boldsymbol{S}_{t+1}, \boldsymbol{Q}_{t+1}) \right\} \right] \tag{5}$$

Where $\boldsymbol{S}_t$ and $\boldsymbol{Q}_t$ are the simulated system state (storage) and inflows at stage t; and $p_{p,q}^t$ is the transition probability (Markov Chain) between inflow class p at time stage t and inflow class q at time stage $t+1$. The $\boldsymbol{S}_{t+1}$ and $\boldsymbol{Q}_t$ values are not subjected to a discrete grid. The reoptimization provides time series of allocation decisions and the corresponding λ values associated to the system's nodes, which correspond to the MROC.

2.3 From MROC values to pricing policies

The ~~time series of MROC values cannot be directly used for the definition of pricing policies: it will be neither operative, nor fair nor secure to implement a pricing scheme in which prices would vary at each time stage. The~~ results given by the SDP algorithm are the optimal allocation policies, benefits and MROC values at each point of the discrete mesh.

Those values vary with the month of the year, monthly storages and monthly inflows. A pricing scheme based on those values would be in theory the most efficient. Highly variable prices are normal in hydropower production, in which deregulated electricity markets' prices and demands vary even during the same day and, in consequence, hydropower producers need to make decisions on very short time stages, being independent of previous choices. However, this situation is distinctly different in consumptive demands, especially in irrigated agriculture. The majority of farmers make most of their decisions in annual or inter-annual basis (area to be irrigated, cropping pattern and so on), being monthly choices dependent on decisions in previous months. Farmers act as risk-averse decision-makers, since errors in the expectations of crop prices, input costs and water deliveries can cause significant economic losses. For those reasons, a pricing policy based on the monthly MROC values would introduce too much uncertainty in the water price and thus in the agricultural sector. On the other hand, the pricing schemes derived from MROC values were conceived as the basis for a process involving discussion, negotiation and approval of a certain simple pricing policy with certain consensus among the stakeholders. As a result, the raw MROC values previously obtained have to be post-processed in order to transform them into simpler *a priori* scarcity-based pricing policies, so that the rule can be negotiated and known beforehand by everybody, allowing farmers to reach accordingly with a more predictable price. Several operations must be carried out to transform the time series of MROC into a step pricing policy depending on the system state variables ~~(S_t, Q_t)~~(t, S_t, Q_t), in which a step function defines the price to be applied each time period. Those operations can be summarized as: MROC values aggregation/disaggregation, MROC statistical analysis, and step pricing policy construction. Although the SDP method was used to obtain the MROC time series, the operations explained below can be used regardless of the algorithm employed (another stochastic one such as SDDP, deterministic optimization or simulation) able to provide MROC time series.

~~Aggregation~~The aggregation/disaggregation of the MROC time series previously obtained is required in order to derive pricing functions at a certain spatial and temporal scale. Regarding the spatial dimension of the intended pricing policy, different pricing schedules for raw water in different zones in the system will better capture the MROC spatial variability. However, the complexity of pricing policies will probably imply greater implementation difficulties. With ~~regards~~ regard to the temporal scale, as stated earlier, pricing policies varying at a lower time resolution (seasonal or monthly) are more accurate than annual ones, although they might also face more implementation problems and higher uncertainty in future prices. Defining a general procedure to aggregate/disaggregate MROC ~~values~~ time series is difficult, since it depends on the desired pricing policy features and each system unique features. An example of aggregation/disaggregation process for the specific features of the desired pricing policy is shown in the case study section.

Once the ~~combined~~ aggregated MROC values are obtained, their cumulative probability distribution can be determined. Several characteristic ~~MROC~~ values can then be chosen using different percentiles of the cumulative probability distribution. Those characteristic values can be used to estimate the MROC-state relationship by: 1) sorting the time series of state variables obtained with SDP according to ~~the respective~~ their respective aggregated MROC values; 2) selecting the MROC-state pairs in which the MROC value was a characteristic one; and 3) organizing the results in the form of state-MROC steps. To sum up, the method presented in this paper can be divided in the following steps:

1. Definition of the main pricing policy features
2. Development of a hydro-economic stochastic programming model of the system
3. Determination of MROC (marginal water values or λ-values) time series at the reference nodes (e.g. main reservoirs)
4. Aggregation/disaggregation of ~~previous~~ MROC time series to calculate the ~~combined MROC time series~~ aggregated MROC values
5. Development of a statistical analysis over the ~~final MROC time series~~ aggregated MROC values to obtain their cumulative probability distribution
6. Building of k steps by:

   (a) Choose k different cumulative probability ~~MROC~~ values (characteristic values)
   (b) Sort according to the aggregated MROC values the system state values obtained in the stochastic programming run
   (c) Obtain, for each characteristic ~~MROC~~ value, the system states associated to it
   (d) Summarize all the possible state values associated to each ~~MROC~~ characteristic value in the form of steps

7. Definition of several step pricing policies based on the obtained steps

Pricing policies can be simulated to assess their performance and to compare them to ~~SDP-derived policies~~the SDP results and to other alternatives such as different operating rules. In case the pricing policies' performance is found to be inadequate, the process must be restarted: the pricing policies' features are reassessed and the build-up and analysis stages must be redone. The most straightforward way to determine its adequacy is to quantify the forgone benefits that the users would be willing to accept as counterpart of using a simpler pricing policy. It is impossible to establish a unique threshold value since it totally depends on the system features. An alternative approach, employed in the case study of this paper, is to compare the performance of the pricing policy with the one achieved by the optimal operating rules expressed by the SDP results. In that way, a pricing policy could be considered as adequate as long as it obtains similar economic returns than those for the optimal policy.

2.4 Case study: Mijares river basin (Spain)

The Mijares river basin is located in eastern Spain (Fig. 2). It is characterized by the existence of several relevant water springs in its headwater (Mas Royo and Babor); the implementation of conjunctive use water strategies to improve water management (Andreu and Sahuquillo, 1987); and the existence of an allocation framework accepted by all the users (SCRM, 1974). Regulated by the Arenós (93 Mm^3) and Sichar (49 Mm^3) reservoirs, surface water is mostly devoted to agricultural purposes (mainly orange trees), with groundwater as complementary or substitutive resource; while urban demands are entirely supplied using groundwater. There are 10.499 ha irrigated exclusively by surface water and 11.622 ha irrigated by surface and groundwater.

The Mijares river simplified flow network is showed in Fig. 3. Although groundwater supply is significant in the lower basin (Plana de Castellon aquifer), it has not been explicitly represented in the optimization model, as there is ~~not~~ no hydraulic connection between the river and the aquifer (disconnected aquifer). Upstream, stream-aquifer interaction is implicit in the inflow (discharge) time series. Seepage equations are also added in certain lower reaches of the river. Consequently, the all-groundwater supplied demands have not been considered, and the mixed-supplied demands have been reduced an amount equivalent to its groundwater supply. The characteristics of each element are showed in Table 1.

Current water management agreements give priority to the supply to the Traditional Irrigation District (ID), which has been using water since the 13th century, over the remaining IDs (established in mid 20th century). In year 1970, before the construction of the Arenós dam (with public funding), an agreement was signed between users to regulate the use of the Sichar reservoir (funded by the Traditional ID) (SCRM, 1974). That agreement established a monthly storage limit for the Sichar reservoir below which only the Traditional ID can be supplied (see Fig. 4). That agreement has continued to be applied after the construction of the Arenós reservoir, but referred to the total system storage (Arenós and Sichar).

2.5 SDP hydro-economic model of the Mijares river

The SDP hydro-economic model comprises all the elements previously described and depicted in Fig. 4. The hydrologic variables $\{q_t, t = 1, \ldots, 12\}$ were discretized into 4 equally-likely intervals per sub-basin, each one represented by a characteristic value. Water demand curves are derived from Alvarez-Mendiola (2012). The minimum flow requirement has been considered as a constraint. A lag-1 Markov chain captures the temporal persistence found in the inflow data. The discrete storage classes adopted were 13 (Arenós) and 7 (Sichar). Minimum flows, demand curves, evaporation and infiltration losses, stream capacities and benefits (obtained as the sum of integrations under all the demand curves) are also taken into account in the model. The model was built using a generalized SDP algorithm developed using GAMS software (Macian-Sorribes and Pulido-Velazquez, 2014). This model was optimized, for an infinite horizon, taking target storages as decision variables.

3 Results

3.1 SDP-obtained benefits, policies and MROC values

The policies and benefits obtained depend on a vector consisting of four variables: Arenós storage, Sichar storage, Upper Basin inflow and Middle Basin inflow. The optimal decisions obtained with the algorithm followed the classic "rule of thumb" of reservoirs in series devoted to water supply: fill the upper reservoirs first, and empty the lower reservoirs first (Lund and Guzman, 1999); as the results empty first Sichar (the lower reservoir) and fill first Arenós (the upper reservoir). In addition, Traditional ID users are subject to greater water deficits compared to the other ones, inverting the current criteria, caused by the river seepage in the lower Mijares streams.

A reoptimization procedure was applied to obtain the time series of MROC values at Arenós and Sichar reservoirs, depicted compared with the sum of storages in Fig. 5. The plots show the same values during most of the historical time series. The slight differences between them found in certain time stages correspond to the opportunity cost of the CC220 ID delivery. Water values increase between 1977 and 1986, period that corresponds to the largest drought suffered by the Mijares river basin. The average MROC value is equal to EUR $0.15\,\mathrm{m}^{-3}$, ranging from 0 to EUR $0.68\,\mathrm{m}^{-3}$.

3.2 Pricing policies in the Mijares river basin

Regarding the aggregation/disaggregation of the MROC time series at Arenós and Sichar reservoirs, the pricing policy used was defined at basinwide scale. This decision has been made considering the proximity of the intakes for the demands and the possibility of releasing water from the two reservoirs to satisfy almost all of them. The chosen temporal scale for the pricing policy was annual, with the same pricing policy for all the months. For simplicity, the state variable for defining the pricing schedule was the sum of the storage in Arenós and Sichar reservoirs, without considering the corresponding monthly inflow. That departs from the SDP formulation, but it is consistent with the current management policies, based exclusively on storages. The aggregation operation driven by these features was simply a non-weighted average of the MROC values at Arenós and Sichar reservoirs, as the MROC values are almost coincident for both reservoirs.

Figure 6 shows the MROC cumulative probability distribution. To establish pricing policies, we sampled the 5 (EUR 0 m^{-3}), 25 (EUR 0.06 m^{-3}), 50 (EUR 0.13 m^{-3}), 75 (EUR 0.24 m^{-3}) and 95 (EUR 0.51 m^{-3}) percentiles. The MROC-storage pairs were then organized in intervals (as depicted in Fig. 7). Each interval or step represents the range of storage values associated to that MROC.

Those steps were used to define the pricing policies. Firstly, the storage space was divided into intervals of 25 Mm^3. A price was then defined for each interval as either the minimum or the maximum or the average over the MROC values associated to the steps found within the interval. As a result, a set of 15 pricing policies was obtained. Figure 7 shows some of them, corresponding to policies regarding maximum between steps (Pricing Policy 1), average (Pricing Policy 2) and minimum (Pricing Policy 3). The remaining pricing policies were based on different combinations between prices obtained in the first three.

3.3 Pricing policy performance by hydro-economic modelling

Each pricing policy was simulated for the 1940–2009 period with a hydro-economic simulation model~~using MatLab~~, previously built using MatLab (Macian-Sorribes, 2012) whose features are identical to the SDP one. This model implements the network showed in Fig. 3 with the corresponding element features (storage capacity, historical monthly inflows, seepage losses equations, etc.), the current demand priority scheme (first the Traditional ID, then the rest), and the current system operation scheme (first fill Arenós, first empty Sichar and avoid as much as possible the streams subjected to seepage losses). More details can be found in Macian-Sorribes (2012). This simulation model calculates at each month the price that corresponds to the available storage, redefines water demands using the demand curves, and then allocates resources using the system's river network and infrastructure. Simulation results are then analysed and compared to the performances obtained with both current and SDP-derived policies (Table 2). Figure 8a shows the time series of benefits resulting from ~~SDP~~SDP-derived policies (the optimal policies obtained from the SDP once interpolated as suggested by Tejada-Guibet in 1993), current management rules and the best pricing policies for the 1940–2009 period.

Regarding Table 2 and Fig. 8a, only slight differences can be found between policies. All pricing policies increase the economic results of current management policies by around EUR 0.70 million per year, being ~~close~~ similar to the ones obtained with the direct use of the SDP policies. For that reason, we consider those pricing policies to be adequate, being not necessary to test complex ones. This situation is caused by the natural robustness of the Mijares river water system and by the homogeneity of the cropping pattern (mainly citrus crops, mostly oranges) found in the basin. The benefit improvement caused by pricing policies is due to temporal ~~relocations~~reallocations: the prices hedge the immediate supplies to allow greater deliveries in the next months. In that way, the deficits and their induced scarcity costs are distributed over several months of slight delivery reductions rather than a single large deficit. As the income losses are non-linear with respect to the deliveries, that deficit distribution improves the total economic return for the system. Despite having the same global benefits, the way they are distributed among the users' changes for all the pricing policies tested, being necessary to take it into account when deciding which one to be implemented.

Focusing on the most severe historical drought faced by the Mijares basin, from year 1977 to 1986 (Table 2 and Fig. 8b), the differences on benefits between the current management and the SDP results are higher (around EUR 1.10 million per year), indicating that SDP-derived policies better hedge available resources against the drought events. To sum up, pricing policy application resulted in greater benefits. Especially in drought situations, the adoption of these strategies would lead to greater economic performances and to a more efficient water use.

4 Discussion and conclusions

This paper presents a method to design an efficient scarcity-based pricing policy based on marginal water values (MROC) derived from stochastic programming. The method is applied to a case study, the Mijares river basin, in Spain. The results show that the benefits from the application of the resulting pricing policies are close to those obtained by the optimal SDP policy for both the entire historical hydrological data series and the drought conditions. By pricing marginal water opportunity costs, water would be reallocated to the highest-valued uses, significantly increasing the total net benefit of water use in the basin (by EUR 0.75 million per year).

The ~~differences between this method and the one proposed in Pulido-Velazquez et al. (2013) consist basically of : (1) using a stochastic programming approach instead a deterministic programming or a simulation one; and (2) obtaining pricing policies via statistical analysis and systemstate sorting according to the MROC values. The use of stochastic programming methodologies implies that the MROC-state relationship obtained reflects an optimal but realistic situation, instead of a non-optimal situation (simulation) or an unrealistic optimal one (deterministic optimization). In addition, the~~ reason why a simple pricing policy is able to achieve similar performance than a complex optimal operating rule in this case study is due to the in-year time pattern possessed by this policy: the majority of the MROC values that determined the water prices for the lower storage levels correspond to start-of-refill ones, while the MROC values associated to high storage levels are start-of-drawdown ones. For that, the prices triggered vary across time in accordance to the refill-drawdown cycle of the system, reproducing in some way the water value annual cycle.

Taking into account the uncertainties associated to the inputs of the model, the predictions concerning the pricing policy performance are therefore uncertain. The most important source of uncertainty is the demand curves, since they directly affect the MROC values and the reliability of the simulated performance of a pricing policy. Given the strong influence of the demand curves in the results, demand curves should be properly estimated and tested.

If water prices are poorly estimated, the result will be an unbalance between resources and demands; this unbalance already happens with the current management of the system during water scarcity periods, in which demand surpasses supply. In that case, the pricing policy should be corrected in an adaptive approach. In cases demand overtook supply due to price being lower than required, water supplies would need to be curtailed according to certain priorities determined either by negotiation or by law, in order to rematch demand and supply. On the other hand, if prices are set too high, financial compensations should be paid to the affected users. In order to avoid those situations, part of the revenues generated by the pricing policy should be employed to increase the accuracy of the estimated demand curves. Furthermore, they may be invested in water security increase or deal with equity issues.

Unlike the method proposed in ~~this paper to obtain pricing policies avoids trial-and-error procedures, whose time requirements are hard to estimate~~Pulido-Velazquez et al. (2013) this one uses a stochastic programming approach instead of deterministic programming or simulation. It also employs a different method to derive the pricing policies based on the MROC and state time series.

The MROC values measure the opportunity cost associated to water use. Therefore, in order to determine the final prices charged to the users, the cost recovery component of the supply costs (O ~~and~~ & M and capital charges) and the environmental externalities ~~have to~~ should be added (Rogers et al., 2002). ~~Final pricing policies require estimating all those components and combining them with the results obtained with this methodology.~~

~~To gain social acceptability and policy equity, mechanisms of financial compensation can be implemented (e.g., Tilmant et al. , 2009). Additional financial resources generated could be them be employed to compensate the users, or to develop adequate infrastructure to increase water security (for example, by financing desalination plant that reduce water scarcity).~~ The main objective in the design of the pricing policies discussed here focuses on the use of water prices as economic instrument for an efficient management of the interaction between supply and demand. The role of pricing for cost-recovery of water services (pricing as financial instruments) will require a complementary analysis.

Comparing pricing policies with water markets, both will be theoretically valid approaches for enhancing economic efficiency in water allocation in the system. Nowadays in Spain water markets are allowed by law, but in practice, only in a few occasions have them been operative, and never in this system. Factors like high transaction costs, farmers' reluctance to participate, low physical connectivity, etc., often prevent more transfers. While the experience and literature on water markets is more abundant, water pricing is clearly underused regarding its potential for dealing with water scarcity. Despite its limitations, drawbacks, barriers and issues for its implementation, water pricing offers some interesting features: contributes to match supply and demand, generates revenues, and maintain customer choices (against command-and control policies). On the other hand, the river basin authority holds the formal control of the system, what is essential for addressing environmental requirements, third party effects, and so on.

Regarding the established methodology and the case study, several conclusions can be drawn:

1. Stochastic programming is a useful tool for estimating optimal policies and MROC time series under hydrological uncertainty. These time series capture and summarize the overall performance of the optimization policies, and can be therefore used to assess pricing policies able to be applied at the basin scale.

2. Pricing policies defined using MROC data series, after statistical analysis and step building, are adequate to enhance system's global economic efficiency. They establish a univocal relationship between the system state (storages and inflows), and a water price based on the marginal value of water in a reservoir, linking the price concept to the MROC one.

3. ~~It can be used to define pricing policies either under general conditions or drought events.~~

Participatory framework processes ~~are needed~~ might be desirable to define the features and characteristics that the ~~desired~~ pricing policies should have, ~~as they condition the MROC aggregation/disaggregation mechanism. These procedures are key milestones for the pricing policy~~ in order to find as much consensus as possible for its implementation.

4. The proposed methodology aims at designing efficient pricing policies. Other issues should be incorporated in the design of a final pricing policy, such as cost recovery of financial costs related to water services and of environmental cost (externalities), as well as equity issues and other social objectives (eg. rural development, environmental protection, etc.).

5. Pricing policy is one of the economic policy instruments that can be implemented to adapt individual decisions to collective goals. We can also apply a mix of them (water markets, pollution taxes, etc.) in order to better reach the social and environmental targets in the management of water resource systems.

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Table 1. Characteristic values of elements of the Mijares river network.

Element	Characteristic value
Arenós reservoir	93 Mm^3 capacity
Sichar reservoir	49 Mm^3 capacity
Upper Basin inflow	138 Mm^3 annual discharge
Middle Basin inflow	55 Mm^3 annual discharge
Traditional Irrigation District	83.5 Mm^3 annual demand
MC Canal Irrigation District	7.6 Mm^3 annual demand
CC100 Canal Irrigation District	16.3 Mm^3 annual demand
CC220 Canal Irrigation District	11.9 Mm^3 annual demand
Minimum flow downstream Sichar	0.2 Mm^3 annual requirement

Table 2. Benefits for the 1940–2009 and 1977–1986 periods with stochastic optimization (SDP), current management rules and pricing policies.

Simulation	Traditional M EUR	MC M EUR	CC100 M EUR	CC220 M EUR	Total M EUR
1940–2009 Benefits per demand and total					
SDP	44.49	4.14	8.56	6.56	63.75
Current policies	46.31	3.60	7.42	5.73	63.06
Pricing policy 10	44.99	4.06	8.29	6.47	63.81
Pricing policy 11	45.00	4.05	8.29	6.46	63.81
Pricing policy 12	45.05	4.04	8.27	6.44	63.81
1977–1986 Benefits per demand and total					
SDP	35.97	3.22	6.80	5.07	51.05
Current policies	42.05	1.69	3.52	2.68	49.93
Pricing policy 4	37.11	3.06	6.09	4.86	51.12
Pricing policy 5	37.11	3.06	6.09	4.86	51.12

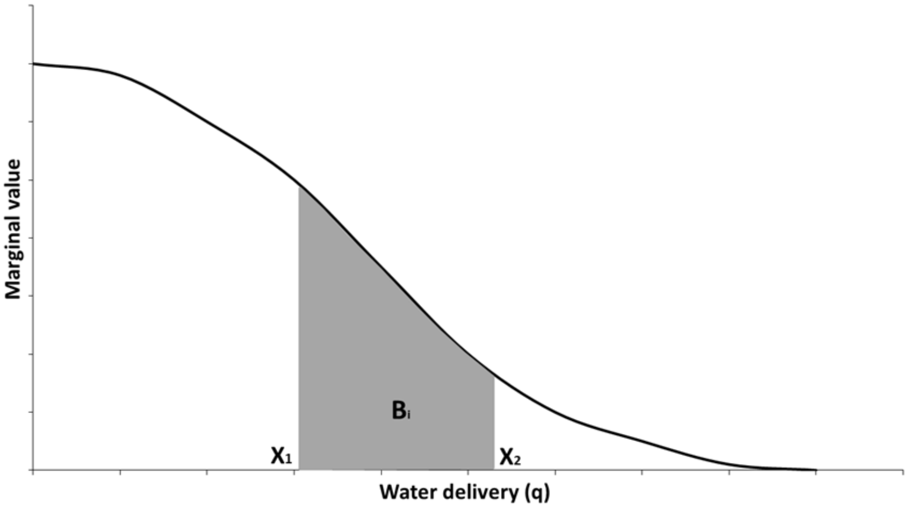

Figure 1. Benefits from an increase of water delivery from x_1 to x_2.

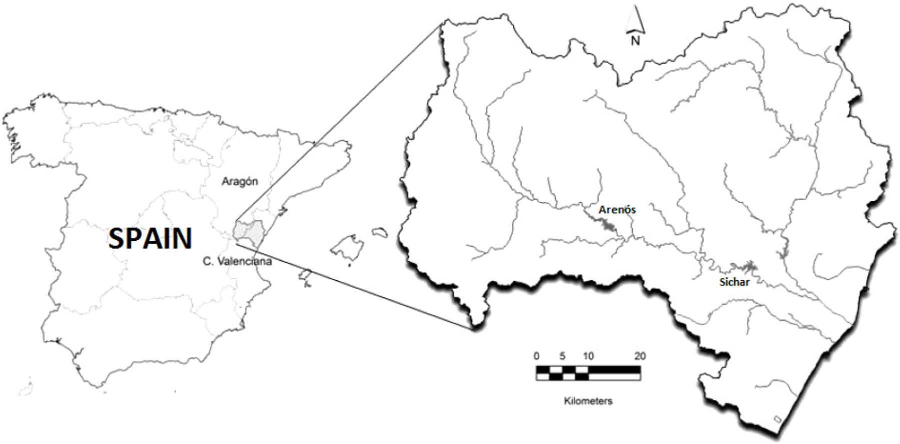

Figure 2. Mijares river basin location (Eastern Spain).

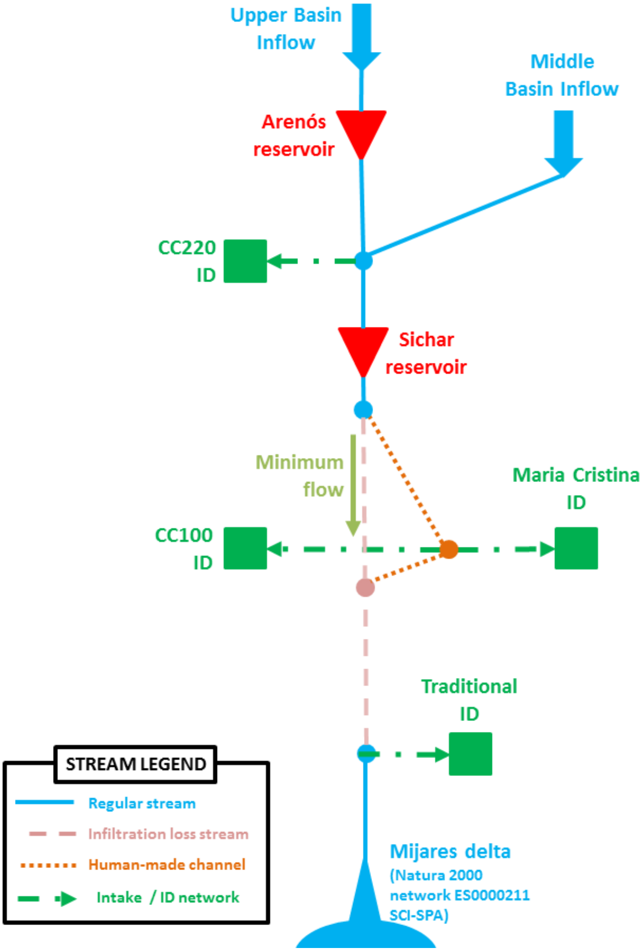

Figure 3. Mijares river network schematic.

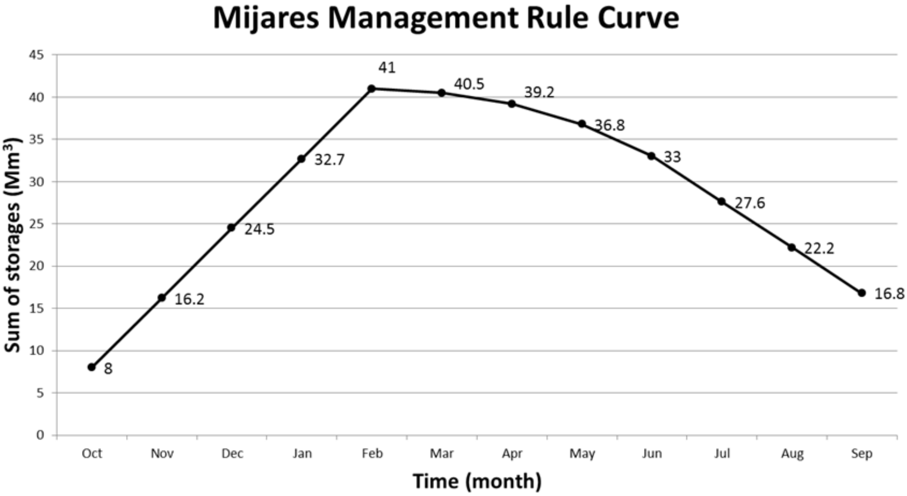

Figure 4. Current management rule curve established in the Mijares river basin.

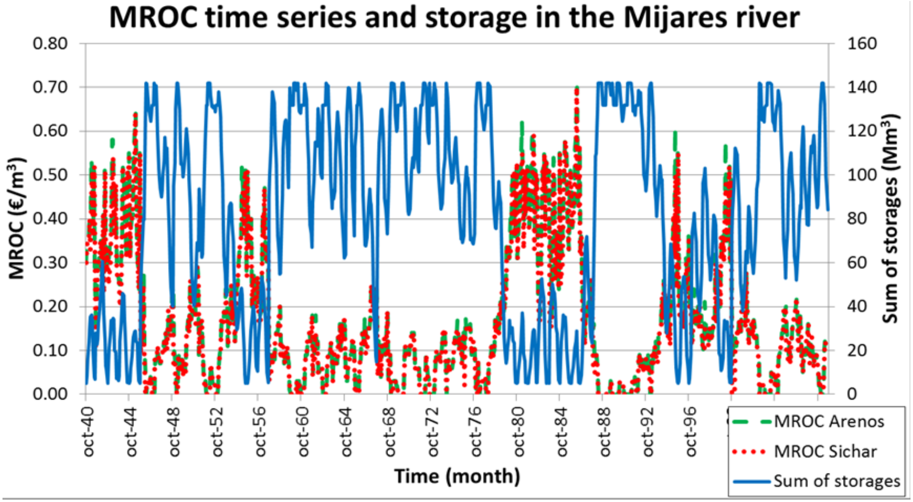

Figure 5. MROC time series and storages in the Mijares river.

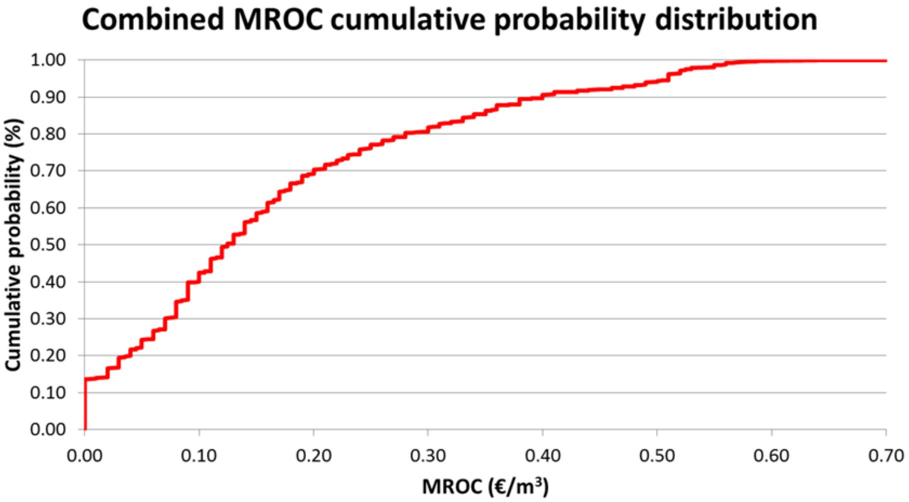

Figure 6. Combined MROC cumulative probability distribution.

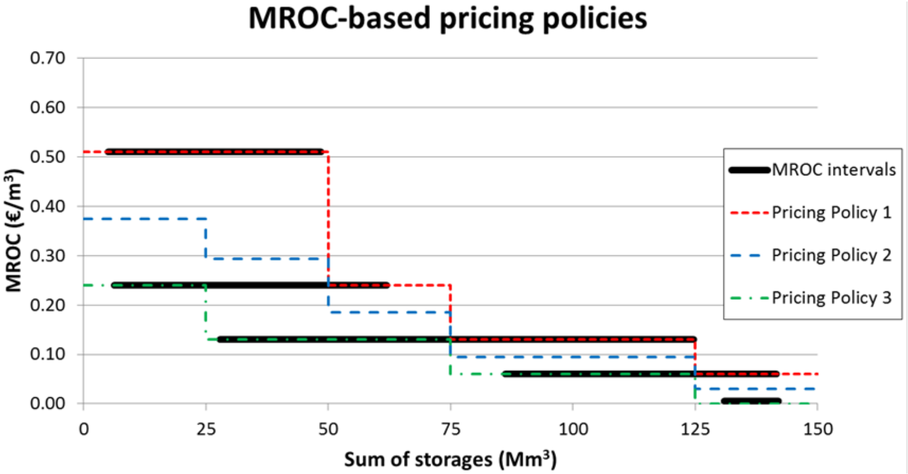

Figure 7. MROC-based pricing policies.

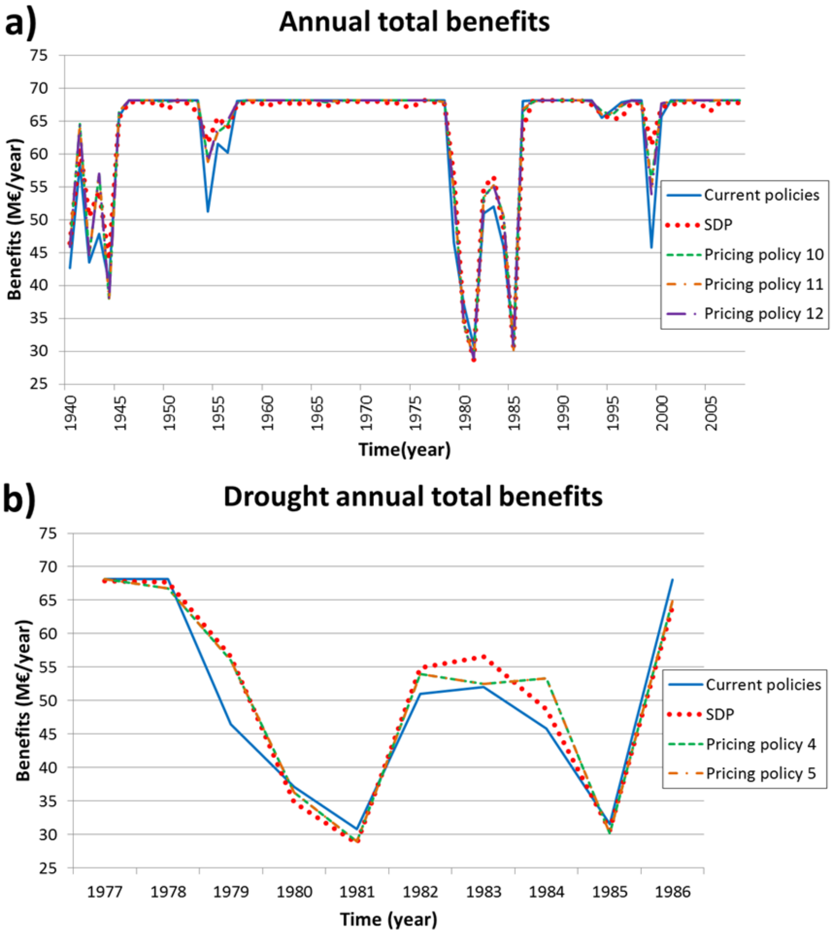

Figure 8. Annual total benefits comparison for the 1940–2009 period **(a)** and for the 1977–1986 drought **(b)**.