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Water Demand Management from an Exergy Perspective. Application to a Spanish River

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This work analyses different water demand management options to assess the monetary losses associated to demand deficits in a region. Diverse water demands priorities were simulated to compare their cost. At this point, the cost to reach a hypothetical Demands Ideal Scenario (DIS) in which water demands are absolutely covered was also considered. It should be a key milestone to be properly developed in the European water management spectrum, since existing normative (the Water Framework Directive, WFD) is mainly focused on the ecological status of water bodies. The assessment was made by applying the Physical Hydronomics (PH) methodology, based on a thermodynamic property called exergy, which evaluates the available energy contained in a water flow, including both its physical and chemical features. A representative area located in the Segre River, a tributary of the Ebro River (Spain), was taken as a case study. Results show that the present priority order when supplying the water demands has the lowest Cost to Guarantee Demands (CGD) that include those derived from the use of water technologies to provide the remaining water.

1. Background

The continuous increment of water demands together with the growing scarcity of water resources have been an important driver of the most recent water policy initiatives in Spain (Spanish Ministry of Environment, 2007). Irrigation is by far the highest consumer in Spain (Iglesias et al, 2008), and it has been subsidized in the past. Then, cheap water granted in the form of concessions could create perceptions in their holders of being entitled to water resources. Nevertheless, per capita consumption is stabled in Spain, and the economic growth is increasingly becoming decoupled from an increment in the water use. Thus, water management has been developed as a broad research and intervention field. From 2003, farmers are more opened to market and to exchange water rights than in last decade (Albiac et al, 2003). Additionally, in many areas, irrigation water demands are nowadays more flexible to be accommodated to the hydrological conditions.
In order to assess the monetary losses due to water deficits, farmers may decide which crops are more profitable to give them priority among the others, where possible. Other alternative consists on supplying those deficits with new resources. A third option is to modify the present priority order (legal one) and to try to find out if lower deficits could be found, so minimizing the cost to guarantee those demands. Current demands priority to take into account in water management was defined in the Spanish Water Law (1999): urban, irrigation, industry (including power generation), aquiculture and recreational uses. Usually, dams are constructed for several uses: urban, irrigation, farming, hydropower and flooding prevention. Regarding to minimum environmental discharges of rivers (ecological flows), they should be respected as a restriction but not as a demand by all future water concessions (except for urban supply) It is important to note that in European regulation, the WFD does not specify an order in the supply of demands, but encourages the implementation of new Basin Plans in which water management is crucial to reach the environmental objectives of the Directive. In this sense, the draft version of the future Ebro River Basin

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Hydrological Plan (CHE, 2012), establishes a priority order to supply demands similar to the one defined in the Spanish Water Law.

2. Methodology

2.1 The Costs to Guarantee Demands. Definition

It was stated by Valero et al. (2009) that any river can be thermodynamically characterized by its exergy value (B, given in kWh), defined as the minimum energy necessary to restore a resource from its reference environment. It can be calculated as the product of its flow (Q, given in m^3/s) and its specific exergy (b, given in kJ/kg of water), a thermodynamic property which depends on chemical and physical parameters of the river and therefore has several components (potential, thermal, kinetic and chemical -inorganic and organic-). The assessment of the different exergy values along a river flow leads to define its exergy profile. In general, the flow Q increases through the river stream due to tributaries, while its quality (b) decreases because of water uses and natural degradation. An exergy gap between two exergy river profiles B_2 and B_1 can be accounted and disaggregated in the corresponding quantity and quality terms, as indicated in Eq. 1.

$$\Delta B_{2-1} = B_2 - B_1 = b_1 \Delta Q + Q_2 \Delta b = \Delta B_m + \Delta B_q \tag{1}$$

Where Q and b are the flow and specific exergy gaps between two exergy states (states 1 and 2), and m and q stands for quantity and quality exergy components, respectively. Through the quantity exergy component (m) it is possible to asses changes related to water discharge flows. Regarding to quality exergy component (q), it includes changes in chemical (chem) components such as inorganic matter (IM), organic matter (OM), and nitrogen (N), as well as thermal (t), kinetic (k) and potential ones (p).
This assessment brings up the opportunity to develop different river exergy profiles which can be represented along its length for different periods and degradation states or scenarios (Valero et al., 2009). As a matter of fact, the contribution of flow resulted to be much bigger than the specific exergy contribution: that is the reason why Exergy (B) and Q representations have similar shapes.
According to the WFD, the Environmental Costs (EC) were defined as those derived to reach the Objective State (OS) of the river (proposed by EU members in accordance with the article 9 of the Directive), but starting from the Future State (FS) of the river, understood as the probable state of the river by 2015. As WFD is focused on the good quality of the future rivers, it does not impose any flow to them in the OS. Water users would have however relevant economic losses if they do not meet their water need to develop their activities. Then, by following the assessment proposed in Eq.1, cost regarding to the deficits with respect to the total supply of the demands, or Cost to Guarantee Demands (CGD) could be assessed by PH. To do that, a Demands Ideal Scenario (DIS) in which water demands are absolutely covered, is the reference, and diverse scenarios could be analyzed, including those in which the use priority is modified. Following the PH guidelines they can be accounted as indicated in Eq. 2, but also disaggregated in the corresponding quantity (m) and quality (q) terms.

$$CGD = B_{DIS} - B_{PDS} = \Delta B_q + \Delta B_m \tag{2}$$

Where the BPDS is the exergy of a proposed scenario with a given priority of water demands, which could or not correspond to the one established in the Spanish legislation. The proposed scenarios are accurately developed next.
In order to assess a monetary cost, the previous exergy gap (physical degradation) has to be translated into an economic one, by means of applying a technology, which usually consumes energy, at a market price. Thus, the Monetary Cost to Guarantee Demands (MCGD) for each scenario and component were assessed as a function of the real exergy difference between degraded (deg) state and restored (rest) state profiles, as calculated by Eq.3.

$$MCGD = En_{price} \cdot \left(\sum_i \sum_j k^*_i \cdot (B_{j,Ideal} - B_{j,SCN}) \right) \tag{3}$$

Where Enprice is the price of the energy, and index j stands for the different exergy terms. Symbol k* corresponds to the exergy cost of the i technologies (Martínez et al.; 2010) adopted to restore the amount of water to cover the demands (desalination and pumping). Anyway, water transfers of groundwater extraction could be alternative technologies in some cases. Amortization and exploitation costs were both considered in the accounting (Fariñas, M.; 2012).

2.2 Water demand management scenarios

The alteration of the priorities of water uses depending on the analyzed scenario mainly implies a variation in water discharge flows, as well as changes in the downstream river composition. And, as expected, it also modifies the water deficit associated to users. Water deficit could also be measured by the "percentage of guarantee" or the contrary one, the "percentage of fail", defined as the ratio between the number of months in which the supplied flow was lower than the real demanded flow and the total amount of considered months.

Different scenarios were simulated:

- *Scenario A*. Present scenario, following the legal priority of demands: Environmental Flow (EF) always remains just after the urban user (UU), as defined in previously exposed legal requirements. Then, agriculture (AU) and hydropower (HU) are in the list of priorities: UU/EF→ AU→ HU.
- *Scenario B*. Dam management is changed in the sense of hydropower has priority with respect to agriculture (UU/EF→ HU→ AU). It consequently provokes a diminution of stored water in the reservoir.
- *Scenario C*. The area is isolated from the grid requirements and then it is strongly dependent on hydropower: the hydroelectric use has the priority: HU→ UU/EF→AU.
- *Scenario D*. Very competitive crops are produced in the area, and the agriculture demand would be the most important one to be firstly supplied: AU→ UU/EF→HU.
- *Demands Ideal Scenario (DIS)*. It corresponds to an scenario A in which all the demands are totally covered. Thus, this means that additional hydropower generation is discharged to fulfil those guarantees.

Note that as hydropower is not a consumptive use, scenarios B and C are very similar to DIS scenario. Main difference will found if delivered water from hydropower is not further used in agriculture (winter periods), and that difference will be translated into a lower level in the reservoir. Then, the analysis is focused next in scenarios A and D.

Composition and physical characteristics of water flows for different hypothetical scenarios were compiled through a hydrographic simulation tool, here the Aquatool software (UPV, 2009). The catchment screen in Aquatool includes the monthly supplied flows, the return and consumption rates due to water use, and also a priority number to be fixed by the user.

The order assigned to demands was allocated from 1 to 3 (1, 2, 3), from the most to the less important demand to be supplied, respectively. Note that Aquatool allows delivering water from a dam to use 2 before the complete demand to use is served. Monthly flows in each stretch of the model, including monthly demands and real withdrawals for different users were compiled. The priority numbers for each scenario and user are summarized in Table 1.

Table 1. Priority orders assigned to different users in scenarios

	Ideal	A	B	C	D
Agriculture	2	2	3	3	1
Urban	1	1	1	2	2
Hydropower	3	3	2	1	3

To illustrate the applicability of the proposed methodology, an example is developed in next section.

3. Case study

3.1 Description

A representative case study located in the Segre river, the main tributary of the Ebro, located in the north-east of Spain, was analyzed. The river flows through the Pallars-Jussá area. Background data to complete the simulation were mainly taken from the competent organism, the Ebro River Management Confederation (CHE, 2012) and from personal communications with its water management office staff. The hydrologic year analyzed was from October 2005 to September 2006. Water demands and its

corresponding deficits (Mm^3) in the selected area are summarized in Table 2: they constitute approximately the 15 % of agriculture demand.
According to the Aquatool simulation, the total storage volume in the reservoir is 2439 hm^3/y. The variation in the reservoir storage volume to supply water demands is 10.82 hm^3. That volume is not negligible but is less than 1 % compared with the already mentioned yearly storage volume.

Table 2. Water demands and deficits in the Pallars-Jussá area, period 2005-2006 (Mm^3)

Users	(Mm^3)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Irrigation	Demands	1.7	0.22	0.09	0.09	0.21	0.99	1.87	4.72	6.84	11.68	9.29	4.43	42.13
	Deficits	0	0	0	0	0	0	0	1.6	1.2	3.5	0	0	6.25
Urban	Demands	0.25	0.23	0.22	0.22	0.2	0.23	0.22	0.25	0.28	0.31	0.29	0.27	2.97
	Deficits	0	0	0	0	0	0	0	0	0	0	0	0	0

Corn and barley are the most cultivated crops in the Pallars-Jussá area. From the economic studies of agriculture in Spain (Albiac et al, 2006), the net economic margin from cereal crops were approximately 0.12 €/m^3 in the area. This means that losses due to water deficits are quantified in 1 M€/y.
Next section summarizes the most representative costs of affronting those water deficits if the priority order of the demands was modified, or if they were obtained from alternative water restoration methods.

3.2 Results analysis

The differences in flow (ΔQ) among diverse scenarios with respect to the ideal one (DIS) is summarized in Table 3. Of course, as the demands are not fully covered, ΔQ is negative for some months. Such as example, the value -2.7 in October, means that there are 2.7 Mm^3 in such month in the Ideal state compared with the scenario A. This water volume is not supplied in scenario A (real scenario).

Table 3. Gaps in river flow. Comparison with the ideal state, period 2005-06 (Mm^3)

$\Delta Q_{SCN\text{-}Ideal}$ (Mm^3)	Oct	Nov-April	May	June	July	August-September	Total
$\Delta Q_{A\text{-}Ideal}$	-2.7	0	-0.31	-0.24	-0.7	0	-3.94
$\Delta Q_{D\text{-}Ideal}$	0	0	-0.31	-0.24	-0.7	0	-1.25

Alternatively, the differences between demands and real supplied water flows in each simulated scenarios state (SCN), that is, water deficits D for those scenarios, are summarized in Table 4.

Table 4. Deficits on supplying demands for different users and water management scenarios, period 2005-2006 (Mm^3)

Use	$D_{Ideal\text{-}SCN}$ (Mm^3)	Oct	Nov	Dec-Feb	Mar	Apr	May	Jun	Jul	Aug-Sep	Total	% Deficit
Agriculture	$D_{Ideal\text{-}A}$	0	0	0	0	0	1.56	1.19	3.49	0	6.25	15
	$D_{Ideal\text{-}D}$	0.85	0.11	0	0.5	0.11	1.5	1.12	3.42	0	7.6	18
Urban	$D_{Ideal\text{-}D}$	0.12	0.13	0	0.11	0.11	0.25	0.28	0.31	0	1.33	45
Hydropower	$D_{Ideal\text{-}A}$	1.35	0	0	0	0	1.56	1.2	3.5	0	7.6	11
	$D_{Ideal\text{-}D}$	0.71	0.11	0	0.42	0.11	1.56	1.2	3.5	0	7.6	11

Regarding the present scenario A, there is no deficit in the urban demand. On the other hand, deficits in summer months exist in agriculture and hydroelectric demands. When the irrigation demand is the first (scenario D) those agricultural deficits increase, and, moreover, a deficit in the urban user emerge.

Once scenarios have been implemented, the total exergy corresponding to the CGD (ΔB_{total}) could be accounted and disaggregated by its exergy components, by considering the equations and specifications given in the Methodology section. Results are summarized in Table 5. The quality component (ΔB_q) is distributed here between chemical (chem), which regards to composition, and potential (p) components.

Table 5. Exergy components of the CGD for different scenarios (MWh) in the case study

$\Delta B_{Ideal\text{-}SCN}$	$\Delta B_{q,chem}$	$\Delta B_{q,p}$	ΔB_m	$\Delta B_{m,\ deficits}$	ΔB_{total}
SCN A	13,803	5,628	20,597	160,739	200,767
SCN D	14,672	5,629	8,695	177,613	206,608

From values summarized in Table 5, and by applying Eq(3), monetary costs based on the PH methodology could be obtained, it water deficits of scenarios A or D were restored by water technologies, most of them based on increasing the water availability (m).

Table 6. Monetary Cost to Guarantee Demands for different simulated scenarios, period 2005-06 (M€/y)

MCGD (M€/y)	$MCGD_{q,chem}$	$MCGD_{q,p}$	$MCGD_m$	$MCGD_{m,def}$	$MCGD_{Total}$
SCN A	6.25	0.6	7.5	57	71.35
SCN D	6.3	0.6	2.5	62	71.4

According to the obtained costs summarized in Table 6, supplying deficits of water supposes in scenario A (real scenario in which legal priority of demands is respected) more than 71 M€/y.
In this respect, the hypothetical unitary costs to totally supply the demands result to be around 1.7 €/m^3, which is not affordable by the farmers.
It was showed in Table 2 that agriculture demands constitute the 93.4 % of total demands (42.13 Mm^3 vs total demands, irrigation plus urban, 45.10 Mm^3 in total). For that reason costs required in the scenario D are similar to cost required in scenario A, besides being a not realistic scenario in which drinking water is not the first priority.

4. Conclusions

New water demands and emerging environmental concerns about water supply and management have favoured new water policies in Spain within a European context.
The cost to guarantee the water demands was studied here through the Physical Hydronomics methodology, based on a thermodynamic property, exergy, which evaluates the available energy contained in a water flow from its physical and chemical features.
A case study based on the Segre river, an important tributary of the Ebro river, was firstly simulated with Aquatool software.
Costs regarding to the deficits obtained when the priority order to supply water demands is modified were then analyzed in this work. Results showed that farmers could not affront the marginal cost to fully cover their water demands.
Furthermore, if agriculture demand is considered the highest priority, those costs are still high and a deficit appears in the urban sector. Thus, present priority order to affront the demands, apart from being the unique option in socioeconomic and sanitary terms, seems to be the most efficient in terms of water management.
A new branch in the PH has been extended here, in which water management options have been tested and therefore some alternative costs to the Environmental Costs of the WFD were assessed.
Upon its comprehensive approach of the “exergy cost concept”, based on the reposition by diverse techniques or technologies of the physical distance between two scenarios, once a river is conveniently modelled, different costs could be estimated in Water Management Planning.

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