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Exergy as a guide to allocate environmental costs for implementing the Water Framework Directive in the Ebro River

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ABSTRACT

The Physical Hydronomics (PH) methodology is a tool to properly calculate restoration cost of water resources (regarding to quality degradation of water as well as water quantity losses) in the framework of the Second Law of Thermodynamics. It is based on the exergy, a thermodynamic property that can be understood as the minimum energy needed to restore a resource from its reference environment. An opportunity that methodology brings up is the development of River exergy profiles which can be represented along the length of the river, for different periods and degradation statuses. Focusing on the Water Framework Directive milestones, the most relevant contribution which is presented here is the assessment of restoration cost among diverse water polluters from physicochemical parameters of the river. The case study which is developed is the Ebro basin, a very representative Mediterranean river in Spain. Figures shown that quality restoration costs, found in the agriculture user resulted to be the highest, except for the organic matter component. If degradation is only focused to water consumption, obviously irrigation use obtained the higher figures. Degradation provoked by the hydroelectric user, never taken into account before in the PH assessments resulted to be the lowest, but increases in wet years. Total investments projected in the draft version of the Ebro River Management Plan seem to be enough to fulfill the environmental objectives projected by the Ebro River basin management authorities.

Keywords: Exergy analysis; Physical Hydronomics; Polluter pays principle; Environmental costs of water; Ebro River

1. Introduction

Additionally to the social and commonly used physical and chemical indicators, the Second Law of Thermodynamics constitutes the basis of an objective methodology able to connect the Physicochemical reality of water bodies with Economics in a simple and understandable way. This methodology, named Physical Hydronomics (PH), takes the thermodynamic property exergy and uses its cost to translate the

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physical and chemical interactions taking place along the river into numerical values, included in kinetic, potential, chemical, and mechanical components, referred, respectively to changes in speed, altitude, composition, and pressure [1,2]. This is made by measuring the costs regarding to the restoration of the degradation provoked by different users along the river course. It hence allows expressing the flows involved in the hydrologic cycle (river discharge, user's demands, returns, and rainfall) as exergy values.

Any river status could be characterized by its exergy value (*B*, given in energy units), defined as the product of its flow (*Q*, given in m^3/s), and its specific exergy (*b*, given in kJ/kg of water). Water exergy is then a thermodynamic property depending on flow and five physicochemical components which characterizes the water condition: thermal, mechanical, chemical, kinetic and potential. These components depend on different parameters. The most important ones are temperature, pressure, composition, velocity and altitude, respectively. The exergy method associates these physicochemical parameters with different exergy component. Since exergy is an additive property, the summing of all those components, expressed all of them in energy units, expresses the exergy of the given water resource and can be understood as their available energy or, as the minimum energy required to restore the resource from its RE. In this respect, PH considers the seawater as the reference environment (RE), that is, the maximum degradation state consisting on water with salts, but without organic matter (OM) because the reference is taken several kilometers far from the coast line [1], where water components are supposed to be absolutely mixed. According to the European Water Framework Directive, the environmental cost (EC) of water regards the alteration of the physical and biological aspects of water bodies due to human activities and represents the average cost damage that water uses impose on the environment and their ecosystems. Thus, an economic analysis is required in order to calculate the costs of water environmental services and economic uses. Such that analysis should be, from the point of view of the authors, based on objective measures and exergy was tested to be an important support to assess water restoration costs.

The mentioned Directive came into force in 2000 with the main purpose of establishing a framework for the protection of inland surface, transitional, coastal and groundwaters. It defines the methods, procedures and indicator parameters for characterizing the condition of water, and the strategies and instruments needed to protect this condition and to regenerate it (if necessary) [3]. However, it provides just general accounting guidelines through physical, chemical, biological, and hydro-morphological indicators. But it does not give specific procedures to asses water restoration cost. Then, the key point developed in this article is the distribution of those costs among water users. It makes possible to allocate economic charges to each of them, in order to restore the degradation they provoke. As starting point, the condition of all water bodies and has firstly to be evaluated, using quantitative and qualitative parameters and identifying the associated pressures, impacts and risks conditioning different water degradation scenarios.

2. Methodology

A natural resource must be changed up to the required physical and chemical conditions depending on the objective of its later uses. Therefore, its thermodynamic value, or minimum work necessary to produce it with a specific structure and concentration from common materials in the environment, is theoretical and equal to the material's exergy value (*B*). It is a thermodynamic property that, in case of water, it is defined by its mass flow and six parameter measurements that characterize its physical conditions: mass flow, as well as temperature, pressure, height, velocity, concentration, and composition. Although each natural resource needs a particular analysis framework, some common stages are needed for a comprehensive water assessment. First, it is necessary to identify the most relevant features of the resource and obtaining its physical and chemical characterization (which makes it differ from the surroundings). Next stage consists on selecting the most suitable RE for the resource (for instance, sea water, that is a proper reference for a fresh water resources evaluation) and, finally, calculating the valuable energy of the evaluated resource [1,2].

Since exergy analysis is carried out by means of thermodynamic macroscopic variables such as temperature, volume and pressure, it can be considered far above other kinds of process evaluations that provoke controversy, due to their special interest in the society, such as the accounting of restoration costs from Economics.

The difference between the exergy of fuels and products determines the energy losses in a system. Then, exergy efficiency (η) was defined by Valero et al. [4] as the proportion of products valuable exergy (*P*) in relation of input energy in fuel flows (*F*) (see Eq. (1)).

$$\eta = \frac{P}{F} \quad (1)$$

In this sense, the unit exergy cost (k^*) was already defined in [4] as the inverse of η as follows (see Eq. (2)):

$$k = \frac{F}{P} \quad (2)$$

The environmental exergy efficiency ($\eta_{\text{env.exerg}}$) of a process was also defined by other authors [5] as the ratio between the exergy of the products and the total exergy consumed in that process as shown in Eq. (3):

$$\eta_{\text{env.exerg}} = B_{\text{products}}/B_{\text{totalconsumed}} \quad (3)$$

While Eq. (3) is based only in thermodynamics definitions, an influence by economic aspects can be seen in Eq. (1) since the purpose of the process is introduced through the fuel and products definitions. Thermoeconomics was then defined as a new discipline joining thermodynamics, economy and ecology [6].

As a direct application of that, PH was defined as a new methodology based on the exergy cost (ΔB^*), or "Real amount of exergy required to produce any physical flow in a system whose limits, aggregation level and subsystems efficiencies have been defined" [4]. This cost was defined as the product of the unitary exergy costs and the exergy gap between two given states, ΔB_{1-2} (see Eq. (4)).

$$\Delta B^* = \Delta B_{1-2} \times k \quad (4)$$

The degradation of a water body depends on the water consumption, but also on its quality deterioration. Then, exergy components (potential, inorganic, and organic) are separately calculated. In general, a higher exergy value means higher quality. It can be easily understood through the potential component, since a higher altitude means more capacity to do shaft work. It can be also seen on the salinity of river waters, which have higher exergy as cleaner they are. It is not however the case of the organic content in water flows. A dirty water flow containing organic wastes will imply high organic exergy (b_{qOM}) rates and it does not mean clean water, but just the opposite [7]. The same reasoning was applied for nitrogen–phosphorous (NP) (b_{qNP}) component.

In order to clarify previous assertion, the full development of specific exergy components is included in Eq. (5).

$$\underbrace{b(\text{kJ/kg})}_{\text{Total.exergy}} = \underbrace{c_{p,H_20}\left[T - T_0 - T_0 \ln\left(\frac{T}{T_0}\right)\right]}_{\text{Thermal.Ex}} + \underbrace{v_{\text{H}_2\text{O}}\,(p - p_0)}_{\text{Mechanical.Ex}} + \underbrace{\Delta G_{\text{f}} + \sum_{\text{e}} n_{\text{e}} b_{\text{chne}}}_{\text{Chemical.Ex}} \underbrace{- RT_0 \sum xi \ln\frac{a_i}{a_0}}_{\text{Concentration.Ex}} + \underbrace{\frac{1}{2}(C^2 - C_0^2)}_{\text{Kinetic.Ex}} + \underbrace{g\,(z - z_0)}_{\text{Potential.Ex}} \quad (5)$$

Different components of the specific exergy are disaggregated in the main components of water flow as follows [1]:

(1) *Potential exergy*: It depends on the change in altitude between the initial and final points in a given stretch of the river ($z - z_{0,}$ given in meters). It also depends on the gravity constant (g, given in m/s^2). This component is always very important because the natural diminution in height along the rivers from source to mouth.
(2) *Thermal exergy*: It depends on the temperature (T, given in Kelvin) and the specific heat of water ($C_{\text{p,H20}}$, given in kJ/kg K or kJ/kg C). This component is especially important when industrial cooling systems are placed into the river.
(3) *Mechanical exergy*: Energy that is possessed by an object due to its motion or its position. It depends on the difference in pressure (p, given in Pascal, Pa) between two points, and the specific volume (v, in m^3/kg). It is important when pumping stations are placed into the river.
(4) *Kinetic exergy*: It depends on the change in speed between the initial and final points in a given stretch of the river ($C^2 - C_{0,}^2$ given in m/s). It is important when water falls appear along the river, and, specially, where the river flows, making possible to it to flow into the sea or into other water bodies.
(5) *Chemical exergy*: accounts for the intrinsic chemical formation exergy of the considered element or compound (named as chemical exergy in Eq. (5)), as well as for the concentration of that substance in the water body under study (named as concentration exergy in Eq. (5)).

The formation chemical exergy regards to the contamination by new substances which are not present in the RE. Thus, the chemical reaction has to be created and balanced, so it depends on the Gibbs Free Energy (ΔG_f, given in kJ/kg), the number of molecules of each new substance e (n_e), and the specific exergy of these substances (b_{ch_ne}, in kJ/mol kg). Main contribution to this exergy value is due to the presence of OM, and nitrogen and phosphor.

The chemical concentration exergy component attends to the different concentrations of chemicals that are on the reference state. Then, this term measures the abundance with respect to the RE. This exergy depends on the reference state temperature (T_0, in Kelvin degrees), and the R (ideal gases constant, 8.314 J/mol K). Defining i as each chemical substance which is present in the RE and in the analyzed state but in different concentrations, this exergy depends on the molar fractions of these substances in the analyzed state (xi), and the activities of each substance i in the reference and analyzed states (a_0 and a_i, respectively). In aqueous solutions, these activities can be considered equal to molar concentrations (mole/volume). Main contributions come from salts concentration (or inorganic matter (IM) contamination in water bodies).

By connecting the exergy costs definition with the guidelines provided by the Water Framework Directive regarding water costs, the EC was assessed by authors in previous works [2] within the PH methodology. This EC was defined by the WFD as the difference between the real state and the objective state (OS) of the river by 2015. As explained, any river state could be characterized by its exergy value (B, given in kWh), as the product of its flow (Q, given in m^3/s) and its specific exergy (b, given in kJ/kg of water) [4]. Hence, the exergy profile of a river could be fully created by a set of Q and b pairs along the river course.

On the one hand, the flow increases linearly from approximately zero, in the point Where the river has its source, until its maximum value, Where the river dies. On the other hand, the specific exergy, that expresses the quality of the river (accounted by physical interactions taking place along the river course), decreases from its maximum value, in the point where the river has its source, to the mouth, were it takes a value close to cero. However, the specific exergy is still positive in this point, since the kinetic and chemical component still remains up to its complete dilution. Then, the theoretical representation of the Q and b is similar to a Gauss bell.

Diverse profiles could be analyzed by applying PH depending on the WFD effectiveness as follows:

- Future state (FS) of the river is understood as the probable state of the river by 2015, starting from present state (PS) of the water stream but introducing the presumably pressures (as an example, the percent of increase in water demands).
- OS is that state proposed by authorities as the good status of the river in order to fulfill with the WFD requirements.
- Natural state (NS) is understood as the state of the river without the presence of economic uses.

Additionally, exergy gap can be disaggregated in the corresponding quantity and quality terms, as indicated in Eq. (6).

$$\begin{aligned} \mathrm{EC} = \Delta B_{\mathrm{OS-FS}} = B_{\mathrm{OS}} - B_{\mathrm{FS}} = b_{\mathrm{FS}}\Delta Q + Q_{\mathrm{OS}}\Delta b \\ = \Delta B_{\mathrm{m}} + \Delta B_{\mathrm{q}} \end{aligned} \quad (6)$$

where ΔQ and Δb are the flow and specific exergy gaps between two given exergy states, and m and q stand for quantity and quality exergy components, respectively.

2.1. Allocation of cost among users

The PH methodology makes possible not only to calculate restoration costs of water bodies, but also to allocate them among different users. To do that, four different statuses were analzsed with an specific hydro-simulation program (Aquatool-DMA), as follows:

- Without users state (WUS) of the river is understood as the state of the river without any demand. It is similar to the NS of the river.
- Urban users state (UUS) is the state in which only urban demands are considered.
- Agriculture users state (AUS) is defined as the resulting state by taking into account only the agriculture demands.
- Hydroelectric users state (HUS) is the state in which only the hydroelectric facilities are taken into consideration. Its reposition cost comes from the energy necessary to restore the power generated by them.
- Dams state (DS). It is a state without uses but with the presence of dams. It was defined in order to separately calculate the affection (ΔB) due to the presence of these infrastructures, necessary to cover different demands. Dams change the available flow along time and space, since they manage the flow coming from the river to be stored or delivered. That lies in a changing gap of flow, and, therefore, in a quantitative degradation of water, that could be negative or positive considering the monthly balance of input and output flows.

Exergy gap between a scenario only with DS and the scenarios reached by each of these users individually individual users state (IUS) were represented by ΔB_i and calculated by applying Eq. (7).

$$\Delta B_i = \Delta B_{DS-IUS} = B_{DS} - B_{IUS} = b_{IUS}\Delta Q + Q_{DS}\Delta b = \Delta B_m + \Delta B_q \quad (7)$$

Additionally, the dams storing effect (ΔB_{dams}) was assessed as the exergy gap between a scenario DS, and the WUS scenario, by applying Eq. (8).

$$\Delta B_{dams} = \Delta B_{WUS-DS} = B_{WUS} - B_{DS} = b_{DS}\Delta Q + Q_{WUS}\Delta b = \Delta B_m + \Delta B_q \quad (8)$$

The exergy gap between the state without users and the real PS, the total restoration exergy gap (ΔB_{TOTAL}) and it should be tested to be approximately equal to the addition of individual gaps (ΔB_{uses})presented above (according to Eq. (9)) as summarized next in an application example.

$$\Delta B_{TOTAL} \approx \Delta B_{uses} = \sum \Delta B_i + \Delta B_{dams} \quad (9)$$

Fig. 1 summarizes that methodology.

It is interesting in that point to give the idea that urban and irrigation users provoke a gap in the quality exergy component due to changes in water composition (inorganic, organic, or nitrogen and phosphorous content are affected by them).

On the other hand, changes in quality exergy due to the hydroelectric uses are found in the potential component. The introduction of this user in the PH analysis constitutes an important novelty of this work. Potential component depends on the height gap (ΔH) in each river stretch. Since this exergy gap varies depending on the kind of hydroelectric technology, an accurate analysis of the main hydroelectric facilities located in the case study, was carried out with the help of monthly data from Endesa [8]. They were considered to assess the degradation provoked by this user

Finally, the monetary costs for quantity and quality components were accounted for by using the unit exergy costs defined for different technologies, as well as the current price of energy [9], according to Eq. (4).

In order to illustrate the applicability of the methodology proposed in this study, the Ebro River basin (which is located in the northeast of Spain) was analyzed. Different scenarios were simulated with hydrological software. Results and main conclusions are summarized in last sections.

3. Case study: the Ebro river basin

The Ebro River (see Fig. 2) is the most plentiful river in Spain, located in the northeast of the country. It as its source in Fontibre (Cantabria, 2,000 m high) and flows into the Mediterranean sea, in a Delta located in Amposta (Tarragona, Catalonian region). Its main drain has a length of 928 km, and its average discharge is around 300 m^3/s. Its basin has an area of more than 85,000 km^2, with about 8,000 km^2 of irrigated land. Most of this surface belongs to Spain. Only 506 km^2 are French and 444 km^2 belong to Andorra [10]. The Confederación Hidrográfica del Ebro is its management organism, framed within the Spanish Ministry of Environment, Farming and Agriculture.

Three main areas can be found along the Ebro River course as follows [11]:

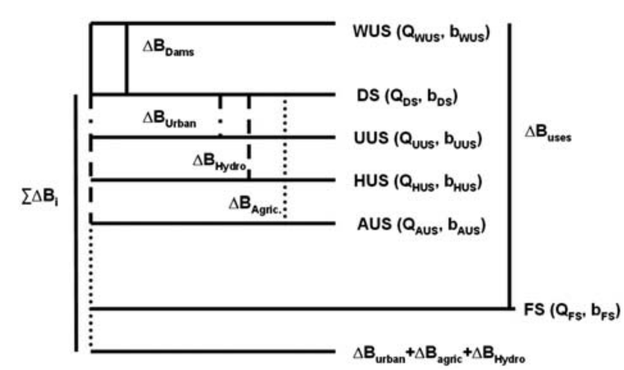

Fig. 1. Distribution of restoration costs among users.

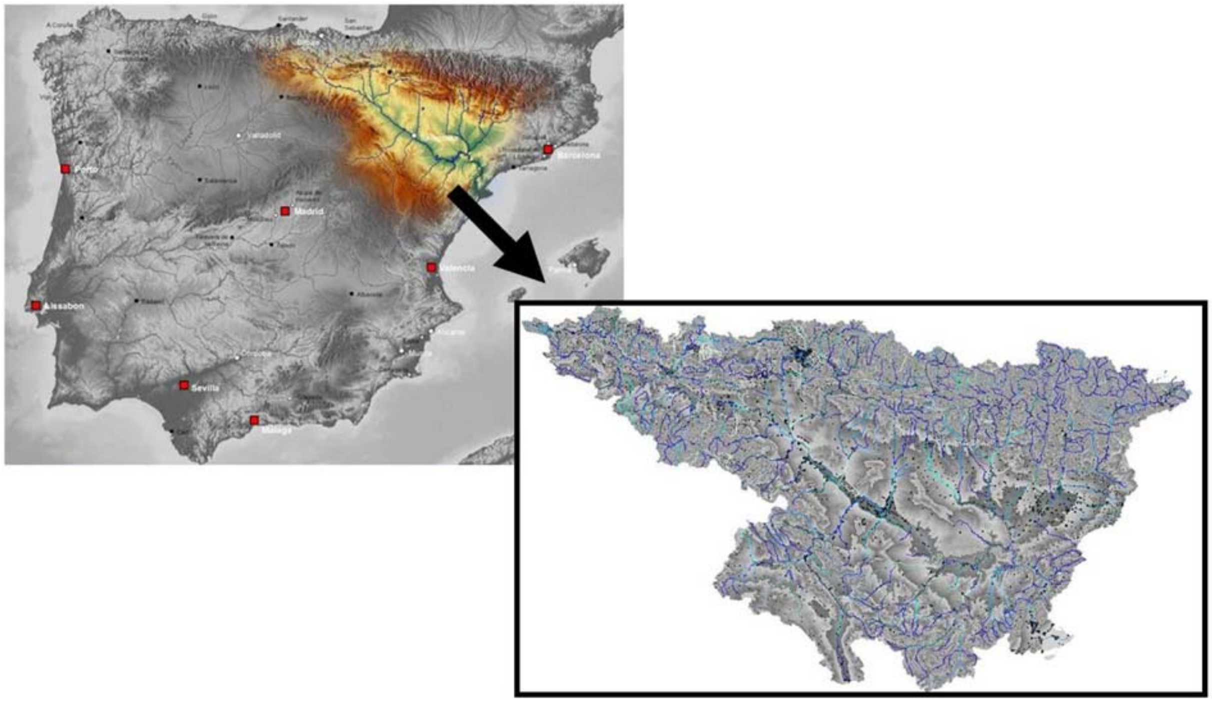

Fig. 2. The Ebro River basin [12].

3.1. The upper Ebro

After the "Ebro" dam, located in the very upper Ebro, the river describes a set of wide meanders, entering in a limestone big area (in Burgos, Castilla-León). Then, the river starts a series of canyons and valleys. In one of these valleys, the Tobalina valley is where the nuclear plant of Garoña is located. The river carries a very big quantity of chlorines and sulfates, and also supports an important contamination which comes from some of its tributaries (Zadorra y Arga), industrial parks (located in Miranda, Logroño, and Tudela), and irrigation returns from la Rioja and Navarra.

3.2. The medium Ebro

After approximately 210 km, the river starts flowing WNW-ESE, along a sedimentary area of tall walls, drawing pronounced meanders, thickets and irrigated crops and. At the end of this hydrologic depression, in the Mequinenza dam, the river reaches its biggest sulfates concentration, due to the limestone, clay, and gypsum landscape basin composition. Tauste and Imperial canals leads on an important irrigation use of this central area.

3.3. The low Ebro

It consists of 150 km after the Segre, the most plentiful tributary of the Ebro. The river starts flowing mainly through Catalonian region, and its discharge is artificially managed in two important and consecutive dams: Ribarroja y Flix. This made possible the presence of great tickets in this area. Before entering into the sea, the Ebro River flows through a narrow, first, and then, wide Oligocene and Pliocene lands, limited by a complex calcareous massif. A second nuclear plant, Ascó, is located there.

The salinity increases as the Ebro enters into the sea (in Amposta, Tarragona), along a plain flooding area (0.17% of slope, approximately). The flow dynamic is basically based on overflowing. Nowadays, the increase in salinity is being notice due to the fact that the Mediterranean Sea is coming progressively into the river, mainly due to the story reduction in sedimentation load provoked by the barrier effect of Mequinenza and Ribarroja dams.

3.4. Practical constrains: collecting data and simulating the basin

An accurate description of quality and quantity data in every river stretch was indispensable in order to achieve the first requirement to carry out the PH application and obtaining the river exergy profiles. It is worth to highlight that the starting point was the great amount of available quantity and quality data from the Ebro basin provided by The Ebro River Basin

Authority (Confederación Hidrográfica del Ebro, CHE) through its website [12], but also supplied by the CHE staff (Hydraulic-Planning office). In spite of this, the Aquatool simulation software [13] also constituted a helpful tool to characterize, in quantity and quality, each stretch of the main course of the river accurately enough. Then, the exergy profiles for the river in different scenarios were represented. The mentioned software, developed by the Polytechnic University of Valencia, contains two independent modules to simulate flow (SIMGES) and quality (GESCAL) patterns, respectively, of a river basin. This specific quality module makes possible to take into account, as others and for several hydrologic years, aspects like aquifers, dams, nonpoint contamination, dangerous substances, or hydroelectric plants.

Input monthly flows data for each year within the 2002–2007 periods were introduced in the Aquatool–GESCAL interface, including some discontinuous discharges coming from the industry. These are necessary to calibrate the simulation results (by comparing them with real data available from quality data stations). In particular, the modelled quality inputs parameters were sulfates, alkalinity, calcium, sodium, magnesium, chlorine, OM, nitrates, ammonium, and conductivity.

Fig. 3 shows the Ebro River basin scheme, as it was prepared to be used in the Aquatool software. The area where Mequinenza and Ribarroja dams are located is shown in detail. In spite of the main course of the river are considered here, the complete Ebro River basin simulated in Aquatool contains: 27 dams, 72 river stretches, 45 water inputs, 111 catchments, and 59 returns.

The calibration of these input flow data constituted an important but not so easy task to be solved. Mass balances were previously carried out with the different water flows by using the SIMGES program module, which deals with water flows. Quality data given by quality control stations along the river course [12] were used to estimate the quality water inflows in river stretches. Water deterioration provoked by uses was calculated from the return ratios for different uses (80 and 20% for urban and agriculture, respectively) [14], as well as from typical elimination ratios of existing Wastewater Treatment Plants and pollution rates for different users [14,15]. Additionally, monthly evolution of temperature, and dam-related data, as evapo-transpiration and level-capacity curves (obtained from [12]), were used.

Quantity and quality flow data were then obtained, per month of each simulated year and stretch. Thus, exergy profiles could be calculated for the simulated users-related states, as it was previously done for the current state of the river. Using Eq. (6), the quantity and quality components for each user could be studied individually. Regarding the exergy contributions, chemical composition was synthesized

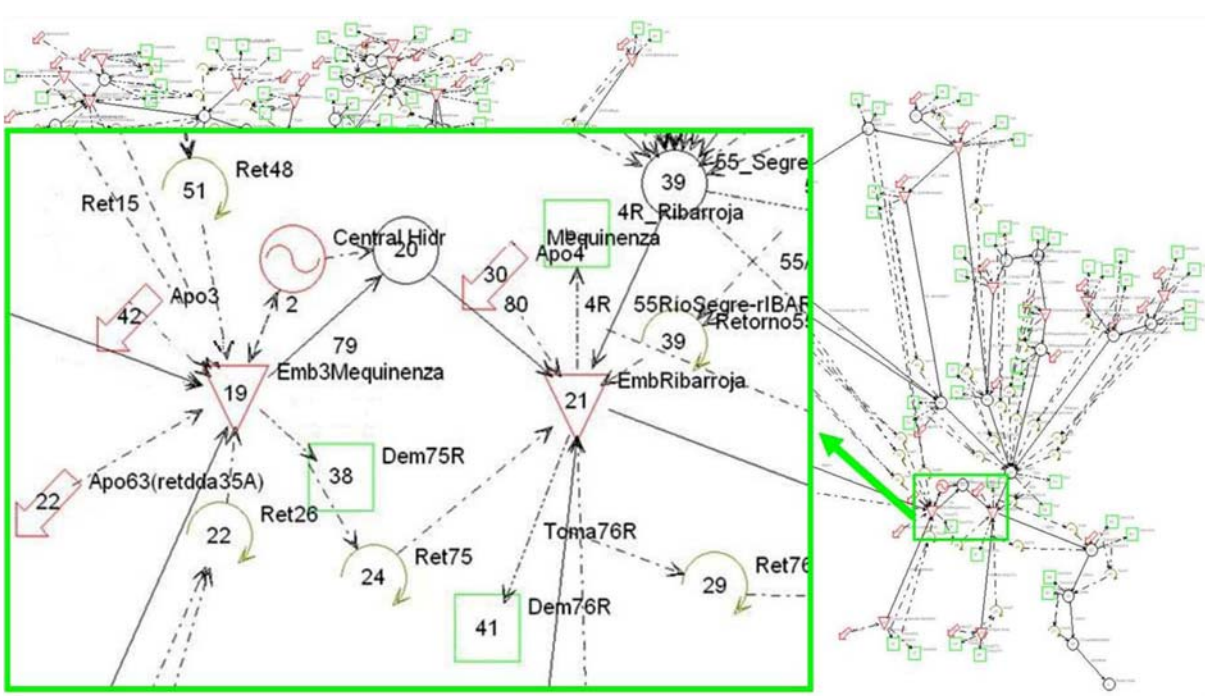

Fig. 3. The Ebro River basin in Aquatool software, and zoom of the lower area.

in: the IM, which stands for inorganic salts and water; the NP component, which accounts for the nitrogen and phosphor in the water flow, in form of nitrates, nitrites, ammonia and phosphates, and the OM. The potential component (p) was also calculated.

4. Results and discussion

The most representative obtained figures are summarized next. As it was expected, the flow increases in the low Ebro. It can be also appreciated that it decreases along the simulated temporal period (see Fig. 4). It was checked that NS remains always higher than the other states. The values of flow increases after stretches 5 and 8, because of the tributaries flowing into the main drain.

Simulation shows that the sulfates concentration is quite high (280 ppm) at the end of the upper river, but reaches its maximum value in the medium Ebro (380 ppm). It is also noticed also an increment in the salinity at the end of the river close to the delta. Regarding to the OM content, in the upper Ebro values close to 4 ppm were found, and close to 6 ppm

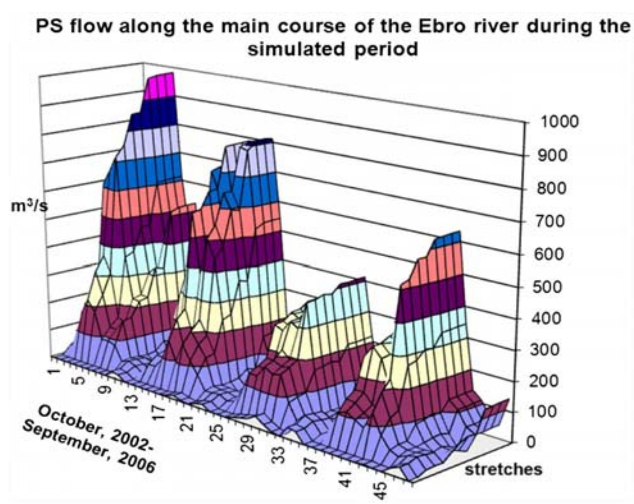

Fig. 4. PS flow along the main drain of the Ebro River.

(maximum value) in the medium course (after industrial parks, and polluter tributaries). Nitrates concentration presents also maximum before the medium course of the river (12 ppm), and increases until 30 ppm in the medium Ebro, due to importance of irrigation in this area. The last significant increment is found at the end of the river, where the nitrates coming from the agriculture returns make the concentration rises until close to 14 ppm. These results are similar to the theoretical description of the basin (see Section 3).

Exergy costs for each component and user were calculated, month by month, and aggregated by hydrologic year. For the sake of clearness, results for the representative dry year, 2005–2006 are summarized in Table 1. Restoration costs for quantitative (ΔB_m) and qualitative (ΔB_q) degradation were considered to share out degradation rates among users. The relative percentages from the total reposition cost, for different users, and for quantity (m) and quality (q) components were also assessed.

The highest total values of quality component gap were found in the hydroelectric user. Focusing on changes in water composition, urban user is the most polluting one, since OM component resulted the most costly to be restored.

Regarding to the dams storage, as it was explained previously, it was considered an exergy gap due to the variation of flow downstream dams. That variation can be negative or positive by considering a monthly balance of flows. During the hydrologic period 2005–2006, total monthly balance of water storage results to be almost zero: the user demands did not change the natural discharge from dams.

Previous results are compared next with the ones obtained for a wet hydrologic year (2002–2003). It is shown that the effect of dams increases, as well as the total reposition cost (see Table 2). Previous results consider both storing and delivering effects in the accounting (that is, not only the months when negative but also the months with positive net flow balances). In case of wet hydrologic analyzed years

Table 1
Exergy components for different users. Dry hydrologic year (2005–2006)

Degrad (ΔB)	% Urban	% Agric	% Hidro	% Dams	Total (ΔB, GWh/year)
$\Delta B_{OM,q}$	83	17	0		65
$\Delta B_{IM,q}$	52	48	0		1
$\Delta B_{NP,q}$	31	69	0		15
$\Delta B_{p,q}$	0	0	100		925
ΔB_q	6	2	92		1,007
ΔB_m	15	85	0	0	1,939

Table 2
Exergy components for different users. Wet hydrologic year (2002–2003)

Degrad (ΔB)	% Urban	% Agric	% Hidro	% Dams	Total (ΔB, GWh/year)
$\Delta B_{OM,q}$	84	16	0		137
$\Delta B_{IM,q}$	27	73	0		2
$\Delta B_{N,q}$	41	59	0		10
$\Delta B_{p,q}$	0	0	100		1,289
ΔB_{q}	5	1	94		1,439
ΔB_{m}	6	84	0	9	4,420

Table 3
Monetary restoration costs for different users (M€/year)

Year	TRC (M€/year)	Total	Quantity	Quality
2002–2003	Urban	459	441	18
	Agric	2,877	2,872	5
	Hydro	113	0	113
2005–2006	Urban	362	342	20
	Agric	1,899	1,892	7
	Hydro	81	0	81

(2002–2003), the yearly balance result to be positive, that means, more water is receiver than delivered by the dam.

Total restoration costs (TRC), and also the costs for each component, given in M€/year, are included in Table 3.

Changes in composition as well as changes in the potential component in the river determine the values of quality TRC. Changes in composition are higher during dry years, because lower discharge in the river increases the concentration of chemicals making more costly to restore water degradation. The higher concentration of chemicals imply higher specific exergy gap between degraded (real) and restored (natural) state, therefore leading on a higher quality exergy cost, coming from composition $\Delta B_{q,chem}$. On the contrary, the drier the year is the lower availability of water to be turbined, and the lower potential component degradation coming from hydroelectric purposes. That implies higher quality exergy cost, $\Delta B_{q,p}$ coming from pressure. That is the main reason why, finally, quality TRC are a little higher during wet years.

Regarding to quantity TRC, they are more important in wet years because of the higher availability of water and the better supplied demands (mostly for irrigation proposes). The more important the withdrawal is the more quantity of water that is finally used and the higher net water losses in the basin. Since quantity restoration costs directly depends on the flow gap between real and natural (without uses) states of the river, the wetter the year is the higher values of quantity TRC.

Total ECs defined by the WFD as the gap between PS and OS were calculated in order to furtherly distribute among diverse water users. To define the OS, data of composition found in [16] were taken into account. They resulted to be around the 10% of TRC already presented. The important gap between both costs stands for the Remaining Resource Cost (RRC), related to the difference between Objective and NSs. Results regarding to the hydrologic year 2005–2006 are summarized next in Table 4.

Any comparison of the results obtained here with existing published official economic figures is somehow complicated, since PH gives operating costs, and only investment cost could be found in the draft version of the new Basin Plan [16].

From the Ebro River Water Treatment Plans (WWTP) installed in last 20 years [12], and considering the WWTP operation cost given by the Instituto para la Diversificación y Ahorro de la Energía [17], a ratio between investment in waste water treatment and operation costs was assessed according to [18].

Previous ratio was considered to calculate exploitation costs from the investment for 2015 given by CHE in [16], already mentioned. These exploitation costs resulted to be around 15–20 M€ per year. That value agrees with EC_q results obtained by PH which are show in Table 4. Reviewing the costs in measures to fulfill Environmental Objectives, together with the

Table 4
RRC in the Ebro River. Comparison with TRC. Year 2005–2006

% Urban	% Agriculture	% Hydroelectric	Environmental costs (M€/year)	RRC (M€/year)
15	81	5	214	2,334

degree of fulfillment of those objectives, it can be concluded that quality Measures Costs (MC_q) resulted to be higher in dry years than in wet years.

5. Conclusions

The main goal of this work was to calculate the water use costs by means of a single indicator (exergy) that could link physicochemical characteristics of the studied resource, water, to economical aspects. Thus, PH methodology makes possible to evaluate the different ecological status of water bodies, and the costs to restore them (or ECs), according to the objectives pursued by the Water Framework Directive. Additionally, it made possible to analyze the seasonal variation of results, assessing not only the contamination rate of water bodies, but also its consumption. PH makes also possible to assess water cost upon a physical objectives but after it also includes economic aspects. But its main advantage lies in a energy-based share of water uses degradation among the economic agents.

The case study was the Ebro River. Despite of the great amount of available data, it was necessary to simulate the basin with the Aquatool-DMA software, for different (hypothetic and real) states of the river. Therefore, the ECs between them were accounted for by comparison of its exergy profiles. Additionally, the costs distribution among users was carried out by the simulation of independent degradation scenarios.

Results show that when degradation is only focused on water consumption, irrigation obtains the highest figures. Restoration costs found in the qualitative component of the agriculture user resulted to be the highest for IM and Nitrogen components, but not for OM components. Degradation provoked by the hydroelectric user resulted to be the lowest, but increases in wet years. The introduction of that user in the PH spectrum also constitutes an important novelty of this work. Finally, the cost to restore the dams storage effect provokes a diminution of downstream river flows in some months and an increase in some others. The net yearly effect is shown for both dry and wet years. Costs to restore degradation from uses in the Ebro river are around 3,000 M€/year. These results do not consider the investment costs of required technologies. Anyway, estimated investment costs with respect to operating costs calculated here are agreed with the ones proposed by the Ebro River Basin Authority in its new Management Plan. Finally, it is important to note that WFD objectives are not so restrictive: if total restoration of the water bodies would be pursued (including restoration of all water consumed in diverse uses), an operating additional cost about 2,000 M€/year more would be required on average with respect to ECs.

There is no doubt about an unavoidable percentage of error existing due to the assessment methodology and the simulation modeling limitations. In any case, PH constitutes a powerful tool for economic agents. As it was explained, the distribution of water restoration cost among users of the basin were both key milestones to be covered by PH. Firstly, PH makes possible the successful share of water uses degradation, helping in taking decisions about water prices. This analysis gives an idea about the feasibility of water prices to be paid by users. According to obtained figures, average price to restore the charges from agriculture and urban users in the Ebro are respectively around 10–34 and 2–4 cts€/m^3. That is useful to realize the fact that, if current price of water should cover this degradation, it could be really expensive for users. The addition of degradation provoked by individual users accounted from individual scenarios agreed with the degradation of the scenarios in which all users are considered at the same time, with an error not more than 20%, for every year in the analyzed period, and for different components (organic, inorganic, nitrogen).

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Nomenclature

AUS — agriculture users state
b — specific exergy (kJ/kg water)

B	—	exergy (kWh)
CHE	—	Confederación Hidrográfica del Ebro (Ebro River Basin Authority)
DS	—	dams state
EC	—	environmental costs
FS	—	future state
HUS	—	hydroelectric users state
NS	—	natural state
OS	—	objective state
PH	—	Physical Hydronomics
PS	—	present state
RE	—	reference environment
RRC	—	remaining resource costs.
TRC	—	total restoration costs
UUS	—	urban users state
WFD	—	water framework directive
WUS	—	without users state
WWTP	—	waste water treatment plant

Subscripts and superscripts

IM	—	inorganic matter
M	—	quantity
NP	—	nitrogen–phosporous
OM	—	organic matter
P	—	potential
Q	—	quality

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