Physical Hydronomics: application of the exergy analysis to the assessment of environmental costs of water bodies. The case of the Inland Basins of Catalonia

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ABSTRACT: The water cycle is governed by the Thermodynamic laws. Therefore Thermodynamics and more specifically Exergoecology [1], that is the application of the exergy analysis in the evaluation of natural fluxes and resources on Earth, could help to build a solid cost structure based strictly on Physics and far away from price policies or subjectivities. Any type of degradation of water bodies along their rivers, lakes, etc. could then be quantified. Moreover, the physical information of the resource can be unified into universal units (energy units), and the monetary conversion of exergy costs is automatic through conventional energy prices. This paper presents a new discipline named "Physical Hydronomics", as a guide to assess environmental costs included in the European Water Framework Directive (WFD).

Keywords: Exergy, Physical Hydronomics, Environmental Costs, River basin, Water Framework Directive.

NOMENCLATURE

A_{DH} Debye-Hückel constant: 0.51 $kg^{1/2}$ $mol^{-1/2}$ for water at 25ºC
B Absolute Exergy (kW)
B_{DH} Debye-Hückel constant:3.287 * 10^9 $kg^{1/2}$ m^{-1} $mol^{-1/2}$ for water at 25ºC
B* Total exergy costs (kW)
b Specific exergy (kJ/kg)
C Velocity (m/s)
COD Chemical oxygen demand
c_p Specific heat capacity (kJ/kg.K)
ERC_l Exergy Replacement Costs derived from quality losses
ERC_t Exergy Replacement Costs derived from quantity losses
FCR Full Cost Recovery principle
GES Good Ecological Status
g gravitational force of the Earth (m/s^2)
I Ionic force (kmol/kg)
IBC Inland Basins of Catalonia
MRC_l Monetary Recovery Costs derived from quality losses
MRC_t Monetary Recovery Costs derived from quantity losses
m_i Molality of the solution (kmol/kg)
$\dot{m}$ Mass flow (kg/l)
n_e Amount of each element e in one kmol of the substance (kmol)
PH Physical Hydronomics
p Pressure (kPa)
q Water flow (l/s)
R Universal gas constant (kJ/kgK)
RE Reference Environment
SC Specific Consumption
T Temperature (K)
v Specific volume of the aqueous solution (m^3/kg)
WFD Water Framework Directive
x_i Molar concentration in 1 kg of solvent (kmol/kmol.kg)
y_i Relative molality (kmol/kg)
z Height (km)
z_i Ionic charge of the ion
ΔG_f Formation Gibbs energy (kJ/kmol)
ϕ_i Effective diameter of the ion (m)

γ_i Activity coefficient
ρ_w Density of the solution (kg/l)

Subscripts
c Concentration term
ch Chemical term
k Kinetic term
m Mechanical term
o Under objective conditions
p Under present conditions
T Total
t Temperature term
z Potential energy term
0 Under reference conditions

1. INTRODUCTION

The new Water Framework Directive 2000/60/EC (WFD) [2] requires that all member states should readjust their water pricing policy by 2010 taking into account among others, environmental costs. These are referred to the alteration of the physical and biological aspects of water bodies due to human activities. Environmental costs are quite difficult to evaluate, at least with the current analysis tools traditionally used by water management policies.

It is well known that standard economics has tried to internalize certain environmental aspects that in fact were considered as "externalities" of the system, giving rise a lot of literature about environmental valuations. Some attempts have been made to measure the value of water and ecosystem services using different approaches. For instance, the hedonic methodology generally traced to Rosen [3], assumes a relationship between residential home or land owner utility functions and ambient water quality within their local watersheds (see for instance Steinnes [4] for details). Another approach is based on indirect methods (e.g. travel cost method), which seeks to recover estimates of individuals' willingness to pay for environmental quality (such as river quality) by observing their behaviour in related markets (see for instance Loomis et al. [5]). The contingent valuation method uses surveys to ask respondents about their monetary values for non-market goods (see the study of Bonnieux [6] for its application to water resources).

Although ambitious, these methods have serious reliability problems since they are based on subjective opinions. Generally, economic reasoning through monetary costs cannot tackle the assessment of environmental costs in a rigorous and comprehensive way. Cost of products and services are calculated by adding the resources required to produce them. But resources are, in turn, the products of a previous process that consumed new resources, and so on. Nevertheless, moving backwards to Nature, it is very difficult to know the fair price of the free resources and services that are continuously taken from it. Usually it is decided that the cost of natural resources is the imperfect price that they will fetch on the market. In this way, the chain of the objectivity of cost is broken since this is also formed by price policies that are not based on Physics. In other words, converting monetary costs into physical costs based on the technical input–output coefficients is only justifiable when no other alternatives and more rigorous methods are available.

Fortunately it is possible to resort to other disciplines, for which the environment is not something strange to it, but it is a part of it. Certainly, for that economy of Physics which is Thermodynamics and for the economy of Nature which is Ecology, there is no unstudied environment. On the contrary, they rely on the nature of the system itself as well as on its interaction with the surrounding environment.

Some notable examples have tried to quantify the embodied energy linked to ecosystem functions through physical based approaches such as Gascó and Naredo [7], Costanza [8], Odum [9] or Faber et al. [10].

The discipline “Exergoecology”, proposed by Valero [1] is starting to be considered as a future rigorous tool for natural resources accounting. The consumption of natural resources implies destruction of organized systems and dispersion, which is in fact generation of entropy (or exergy destruction). This is why the exergy analysis can perfectly describe the depletion of natural capital and specifically, the degradation of water bodies.

The application of the exergoecological discipline to the natural resource “water” will be named from now on as “Physical Hydronomics” (PH).

2. THE EXERGY OF WATER BODIES

The thermodynamic value of a natural resource characterized by its specific properties like structure or concentration is defined as “the minimum work (exergy) needed to produce it from common materials in the reference environment”. The exergy of a system reflects its thermodynamic potential for not being in equilibrium with the environment or, more precisely, for not being in a dead state related to the RE. This RE must be determined by the natural environment and is defined as one in which its height, pressure, temperature, composition and other properties has zero exergy.

The best suitable environment taken as reference for calculating the exergy of water bodies is seawater. Seawater is the last drain where all waters arrive to. Once fresh water is mixed with salty water from the sea, its usefulness for human, agricultural or industrial uses is practically lost. Thus, a water body has maximum exergy, when it firstly appears as rain water, and decreases its exergy as it flows to the river mouth, where it loses it. On the other hand, seawater can be seen as a huge water reservoir from which any quantity and quality of water can be obtained with the appropriate technology fuelled with enough primary energy.

2.1 Specific exergy

The specific exergy of a water body is defined by its mass flow and six measurable parameters characterizing the thermodynamic status of water: temperature, pressure, composition, concentration, velocity and altitude [11]. The exergy method associates each parameter with its exergy component: thermal, mechanical, chemical, kinetic and potential. The model assumes the approximation to an incompressible liquid where the exergy is defined through the mentioned components.

$$\begin{aligned} b_T\,(kJ/kg) = {} & \underbrace{c_{p,H_20}\left[T_p - T_0 - T_0 \ln\left(\frac{T_p}{T_0}\right)\right]}_{b_t} + \underbrace{v_{H_2O}\left(p_p - p_0\right)}_{b_m} + \\ & \underbrace{+\left[\sum_i y_i(\Delta G_f + \sum_e n_e b_{chne})\right]_p - \left[\sum_i y_i(\Delta G_f + \sum_e n_e b_{chne})\right]_0}_{b_{ch}} + \\ & \underbrace{+RT_0 \sum x_i \ln\frac{a_i}{a_0}}_{b_c} + \underbrace{\frac{1}{2}\left(\frac{C_p^2 - C_0^2}{1000}\right)}_{b_k} + \underbrace{g\left(z_p - z_0\right)}_{b_z} \end{aligned} \tag{1}$$

Where subindex “0” denotes the water properties of the reference environment and “p” of the water body under consideration.

Each component must be separately calculated. The sum of all components expresses the specific exergy of the given water resource and can be understood as the minimum energy required to restore the resource from the reference. Each component of Eq. 1 will now be explained in detail.

Thermal Exergy

Thermal exergy (b_t) depends on the specific heat capacity of the aqueous solution c_{pH2O} (kJ/kgK) which could be assimilated to that corresponding to pure water (for river and lake waters) and its absolute temperature, T_p (K). This term is very important since the RE (seawater) is a huge reservoir in which temperature does not change as dramatic as river courses.

Mechanical Exergy

The mechanical exergy (b_m) term is calculated from the specific volume of the aqueous solution (v) and the pressure difference with the RE. This component could be representative if pumping stations and buried pressure piping systems are analyzed in the study, as well as water collected in reservoirs.

Potential Exergy

The potential exergy (b_z) term is calculated taking into account the height z_p (km) where the measurement was taken. Constant g represents the gravitational force of the Earth (9.81 m/s^2). Although this term is quite important in the river source of a basin, special attention should be paid in the case of reservoirs with installed hydropower utilities: this potential exergy will be converted successively into power. Obviously seawater height is zero.

Kinetic Exergy

The kinetic exergy (b_k) is calculated by taking the absolute velocity C_p (in m/s) at the sampling point. Unless the sampling station is located in rapids and/or hydropower canals, this term is not relevant. The velocity in the RE C_0 is zero by definition.

Chemical and concentration Exergy

Any component diluted in a given sample of water has a chemical composition and concentration that contributes to the total exergy of the mixture. The first term will only appear for those substances in the water body that are not present in seawater.

The chemical exergy (b_{ch}) of any chemical compound can be easily calculated with the formation Gibbs energy (ΔG_f) of the substance considered (kJ/kmol), the amount of kmol of each element e contained in one kmol of substance i (n_e) and the standard chemical exergy of the element (b_{chne}) measured in kJ/kmol of element e, that can be found in [12]. This exergy has to be calculated for all substances in the water body and summed up according to its relative molality (y_i), measured in kmol of substance i per kg of water.

In addition to the chemical exergy, the concentration of the substances in the water body have to be compared with their concentration in the reference state. This term is the most complex to calculate since two different contributions have to be considered: one corresponding to the dissolved inorganic and another corresponding to the organic substances. Activities of any substance i on water (a_i) are rather used than molar concentrations (x_i), since we are dealing with solutions.

The dissolved inorganic substances are evaluated from their direct measurement in the river throughout the sampling stations. Starting from the measured concentration of each electrolyte, the activity of each of them could be calculated by applying the simple formula:

$$a_i = \gamma_i \cdot m_i \qquad (2)$$

where γ_i is the activity coefficient, and m_i is the molality of the i substance. The first term could be calculated by applying the Debye-Hückel theory for dilute aqueous solutions that explains the electrostatic interactions:

$$\ln \gamma_i = \frac{-A_{DH} \cdot z_i^2 \sqrt{I}}{1 + B_{DH} \cdot \phi_i \cdot \sqrt{I}} \qquad (3)$$

where A_{DH} and B_{DH} are constants that only depend on temperature for aqueous solutions, z_i is the ionic charge (valence), ϕ_i is the effective diameter of the ion in the solution, and I is the ionic force that takes into account the effect of the other ions in the solution:

$$I = \frac{1}{2}\sum_i m_i \cdot z_i^2 \qquad (4)$$

The dissolved organic substances are estimated from the measures related to the organic material in water. When the measure of the chemical oxygen demand (COD) is available, a combustion reaction is supposed assuming that organic material is completely biodegradable. Then, it can be represented by a generic formula CH_2O (the basic molecular combination of sugar). However, COD is not adequate when organic concentration is very low, as in rivers. In these cases, the commonly given parameter is the total organic carbon (TOC). The measured carbon is assumed to be in the form of the above mentioned molecule. Finally, note that organic nitrogen and phosphorus measured in the river are also accounted for here because they are assumed to have an organic origin.

In summary, it is clear that through exergy, the physical properties of any natural resource can be assessed with the same units (energy units), ensuring the homogeneity of the results. Furthermore, exergy has the ability to aggregate or disaggregate the physical features of the good increasing the analysis capacity and giving more flexibility to the study.

2.2 Absolute Exergy

Once the specific exergy (b) is properly calculated, the absolute exergy of a water flow could be obtained. The absolute exergy in power units (kW) can be easily calculated with the following equation:

$$B\,(kW) = q(l/s) \cdot \rho_w (kg/l) \cdot b(kJ/kg) = \\ = \dot{m}\,(kg/s) \cdot b(kJ/kg) \qquad (5)$$

Where q is the water flow of a river/channel/pipe, ρ_w is the density of the aqueous solution and $\dot{m}$ the mass flow.

2.3 Exergy profile of a river

The exergy profile of a river along its course has a characteristic curve which is quite similar for all of them. This fact can be explained analysing the typical profiles of specific exergy and water flow of rivers.

The ideal and simplified specific exergy profile of a river is illustrated in Fig. 1a. At the river source, water is found at the highest elevation and at the most pure state, therefore its physical and chemical exergy are the highest at that point. As it flows into the mouth, the water body loses height and purity and therefore its specific exergy decreases until it reaches the point of minimum exergy (maximum degradation) which is the sea (reference environment). The water flow usually follows exactly the opposite path (Fig. 1a): minimum at the source and maximum at the mouth. Both effects together give an ideal total exergy pattern of the bell-shaped curve given in Fig. 1b.

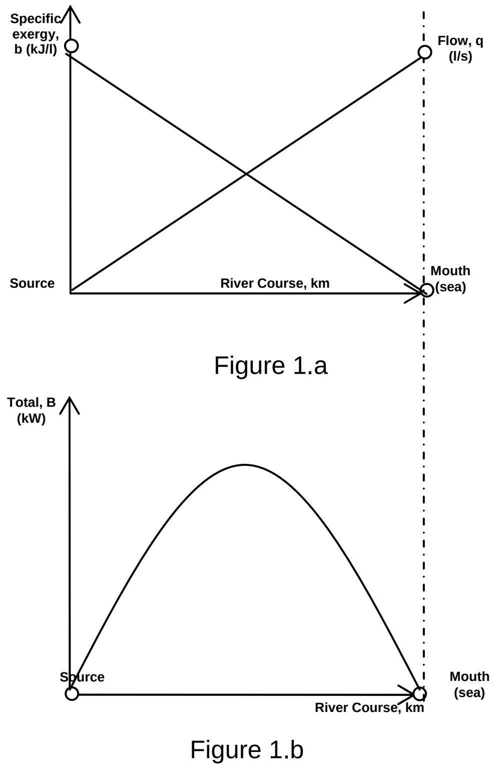

Figure 1: Typical specific exergy, water flow and total exergy profiles of “ideal” rivers

This ideal pattern of Fig. 1b is modified in present rivers, since the specific exergy and water flow lines do not follow a perfect straight line. The existence of tributary rivers, filtrations to aquifers, catchments to diverse consumptive uses, solar evaporation, spill outs, etc. create positive or negative deviations in Figs 1a and 1b, i.e. in the quality and quantity of rivers.

It must be pointed out that the profile of rivers is a function of time because of their torrential nature and seasonal uses. Therefore, in practical terms, the exergy profile of a given river is better described monthly or even daily.

3. PHYSICAL COSTS

The sum of the obtained values for each exergy component is the total exergy that can be understood as the minimum energy required for restoring the resource from the sea. However, real man-made processes are far from the ideal conditions because of inefficiencies of our technology resulting in irreversibilities. Energy requirements to obtain a resource are always greater than those dictated by the Second Law. In order to overcome that problem, we must include the real physical unit costs known as Exergy Replacement Costs (*ERC*) in the thermodynamic evaluation of resources [13]. These are defined as the relationship between the energy invested in the real process for obtaining the resource and the minimum energy required if the process were reversible. It has a dimensionless value and measures the number of exergy units needed to obtain one unit of exergy of the product. Generally, the exergy replacement cost is tens or even hundreds of times greater than its exergy content. The real physical value of a resource (total exergy cost) B^* is determined then by the sum of each specific exergy component (b_i) multiplied by the unit exergy replacement cost (ERC_i) of the process to restore that physical feature of the resource as in Eq. 6.

$$B^*(kW) = \dot{m}\sum_{i}^{n} ERC_i b_i \qquad (6)$$

The knowledge of suitable technologies, with their range of application and specific consumptions (SC) is mandatory to calculate *ERCs*. Once SC has been reviewed (including energy consumption for producing plant consumables) for all of them, the relation between the real energy cost and the energy required in an ideal reversible process (exergy) gives us the unit *ERC*.

3.1 Exergy costs oriented to WFD objectives

The total exergy costs B^* give an indication of the actual effort we should make to restore the river because of its departure in quality and quantity from the sea. It measures the cost for producing water (through desalination) and pumping and transporting it to the point under consideration, with the given available technology. This measure is useful for establishing an objective guide for water management, as it offers a map of maximum costs in a certain territory.

However, if the objective is to calculate the degradation costs of a certain water body or flow due to the anthropogenic presence, those previous costs are not representative because it is not necessary to extract, desalt and pump seawater to improve existing waters to a better status. In other words, the interest resides in comparing the exergy difference obtained with the total exergy profiles of water courses under present (Bp) and any other objective conditions (B_o).

One possibility is to compare existing waters with a desirable state labelled as the “good ecological status” (GES) of water bodies, as promoted by the WFD. The latter would be the state at whose achievement all the efforts should be aimed: in this way, with the exergy difference between present and objective qualities, it could be evaluated in a physical manner the Action Plan that EU Member States will have to apply in order to reach the GES objectives for water bodies in 2015, a WFD mandatory. Anyway the definition of this profile (B_o) will remain open to technical/legal agreements.

GES is quite ambitious because it includes both the quality and quantity of the water body and its ecological status as a life support system. Physical Hydronomics will only deal with the physical status of the water flow, without accounting for living organic forms. Jorgensen [14] through its "ecoexergy" has studied the exergy of organic systems. Ecoexergy could also be considered as an additional component in our approach for establishing biological costs. However, given the still existing distance between both methodologies this part needs still to be refined.

Once both states are established, the idea is to calculate the exergy cost of the exergy drop ΔB that was generated between the present and objective situations provoked by human activities. This gap has to be restored by means of the available technology (in energy terms) and obviously will have a cost. Furthermore, it could be divided into the quantitative and qualitative terms, as in Eq. 7:

$$\Delta B = \dot{m}_o \cdot b_o - \dot{m}_p \cdot b_p = (\dot{m}_p + \Delta\dot{m}) \cdot (b_p + \Delta b) - \dot{m}_p \cdot b_p \cong \dot{m}_p \cdot \Delta b + \Delta\dot{m} \cdot b_o = \Delta B_l + \Delta B_t \quad (7)$$

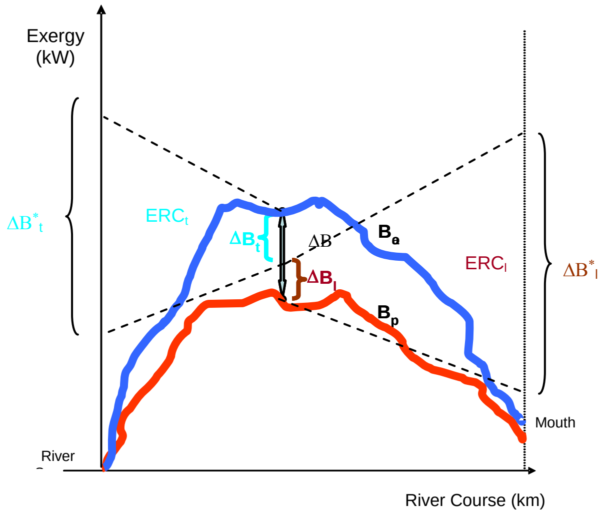

Figure 2: Restoring the objective situation by disaggregating qualitative and quantitative effects.

The exergy replacement costs (*ERC_l and ERC_t*) derived respectively from both exergy gaps are defined as follows:

- In order to restore the exergy gap ΔB_l due to the loss of quality of the water course diverse purification technologies have to be applied up to the desired limits. Diverse tertiary treatments will be the most adequate in this case since it is assumed that in the EU all waters are previously treated in seawage plants.
- For eliminating the exergy gap ΔB_t due to the loss of quantity of the water course because of human consumptions, we have to desalt seawater in a desalination plant located in the river mouth, and then pump out this water flow to its corresponding point in the water course.

The conversion of physical into monetary costs is very simple because they are obtained by multiplying the energy demand (kWh) by the current energy price ($ or €/kWh). If investment and O&M costs are also added to each technology, the resulting monetary recovery costs (MRC_t and MRC_l) could serve as an objective reference for assessing the environmental costs. In this way it could be analysed the fullfilment of the Full Cost Recovery (FCR) principle of the WFD, disaggregated by the different economic sectors and identifying the remaining subsidies in the water sector (see Fig. 3).

The main drawback of the PH methodology is the huge amount of information needed (specially the quality parameters). The model can be locally applied to rivers, flows and lakes or reservoirs with sampling stations, but it is very difficult to obtain all the information necessary to apply the model accurately on a global scale. Nevertheless, if enough data is available, PH could become a fundamental tool for assessing the real physical cost of water.

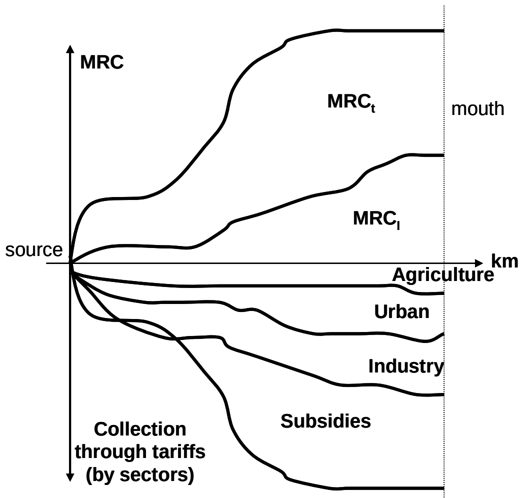

Figure 3: Degree of recovery of environmental costs dissagregated by economic sectors.

3. APPLICATION OF PHYSICAL HYDRONOMICS TO THE IBC

This new methodology is currently being applied to the Inland Basins of Catalonia (IBC). The study is under the framework of a three-phase project resulted from an agreement between CIRCE Foundation and the Catalan Water Agency. The final objective is to use those calculated physical costs as a guide to apply the environmental costs proposed by the WFD. It is understood as the key for further applications in other areas, as for instance the Catalan Basins of Ebro (objective followed in subsequent phases), other regions of Spain (through the corresponding agreement with River basin Authorities or Regional Entities) and even other countries. Next, the main features of the study are briefly outlined.

For the accomplishment of the project, a water network (with about 90 points) has been firstly created with the main water courses, water supply piping systems, reservoirs, desalination plants and aquifers. Water quality data and flows required for the present status have been obtained from existing sampling stations for the hydrologic year 2003-2004. The exergy value of present water courses has been obtained by the addition of thermal, mechanical, potential and chemical (organic and inorganic) components. Regarding the objective status, quantity and quality flows for the hydrologic year under analysis, have been calculated following the methodology adopted to restore water flows into its natural regime (without human action) [15].

In order to calculate exergy costs, figures from existing water treatment plants are being collected (wastewater, water supply, pumpings, desalination) and computed in the area. Those costs are being disaggregated, when possible, by diverse human activities (urban, industry, agriculture, farming, energy, recreational).

Figure 4 shows an example of the profiles obtained for the Llobregat river.

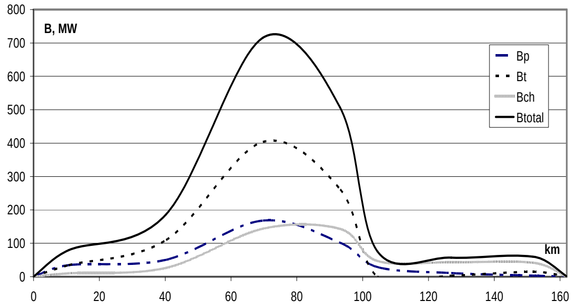

Figure 4: Present exergy profiles (total, thermal, potential and chemical) of the Llobregat river in december 2003.

5. CONCLUSION

In this paper, the basic theory of Physical Hydronomics has been presented for the first time. This research field makes use of general and simple concepts coming from Physics, more specifically from Thermodynamics in order to assess physical costs of water.

No matter the value we give to water, there is no global scarcity of water in the planet, but local and temporal quality and quantity scarcities. Local scarcity problems are solved by investing energy and money. Those energy costs are what Physical Hydronomics intends to assess from an objective and comprehensive way. With the help of Thermodynamics, through the exergoecological approach, we have the ability to propose a universal, transparent, and objective cost structure that is able to show the real physical cost of water. Physical Hydronomics can play an essential role by providing clear and accessible information on the available quantities and qualities of that resource. Furthermore, it opens a new way of approaching the Full Recovery Principle of the WFD.

Physical Hydronomics does not intend to substitute any other cost analysis approach. Monetary analysis and other methodologies which are able to calculate for instance biological costs are also essential for the complete evaluation of a water body. PH should complement them in order to develop the economic analysis of the WFD from a multidimensional and multidisciplinary perspective.

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This study is the first milestone of the pioneer initiative of the Catalan Water Agency of connecting Physics with Economy for assessing water costs.

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