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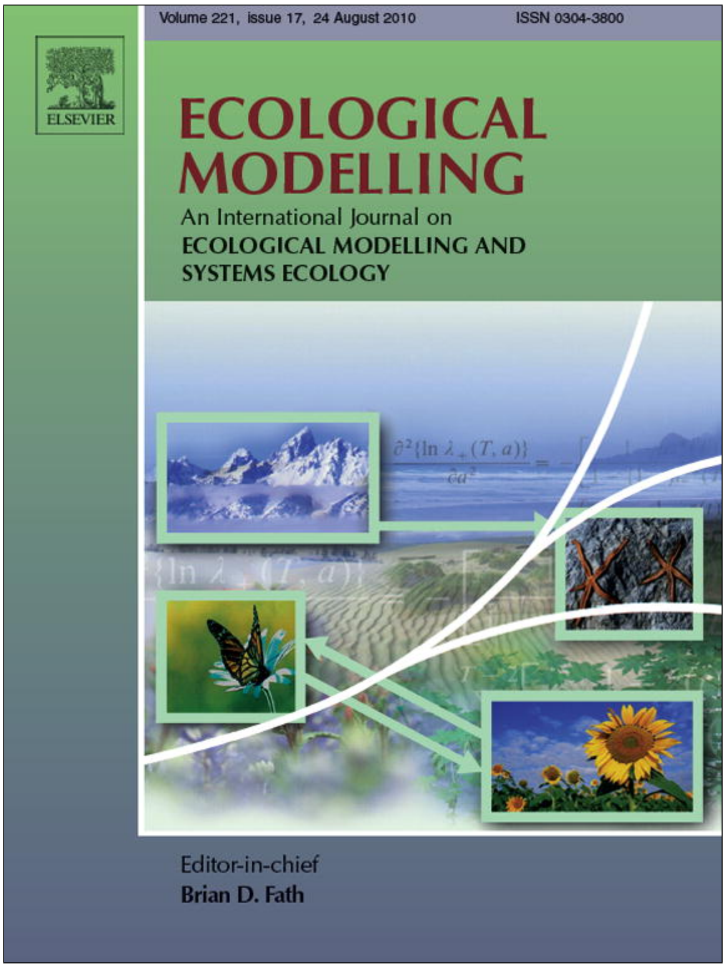

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Emergy analysis applied to the estimation of the recovery of costs for water services under the European Water Framework Directive

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ABSTRACT

In this paper, the European Union's Water Framework Directive 2000/60/EC (WFD) that is intended to foster protection of water resources is examined, focusing on the improvement of ecological and chemical quality of surface and groundwater. The WFD includes the concept of full cost recovery (FCR) in accordance with the Polluter-Pays Principle, as one of the tools of an adequate and sustainable water resource management system. The WFD defines three different costs associated with water: resource costs (RC), financial costs (FC), and environmental costs (ECs).

The FCR of water is examined from a biophysical perspective using emergy evaluation to: (1) establish resource values of water from different sources, (2) establish the full economic costs associated with supplying water, and (3) the societal costs of water that is used incorrectly; from which the resource costs, financial costs, and environmental costs, respectively, can be computed. Financial costs are the costs associated with providing water including energy, materials, labor and infrastructure. The emergy based monetary values vary between 0.15 and 1.73 €/m^3 depending on technology. The emergy based, global average resource value (from which resource costs can be computed) is derived from two aspects of water: its chemical potential and its geopotential. The chemical potential monetary value of different sources such as rain, groundwater, and surface water derived from global averages of emergy inputs varies from 0.03 to 0.18 €/m^3, depending on source, and the geopotential values vary from 0.03 to 2.40 €/m^3, depending on location in the watershed. The environmental costs of water were averaged for the county of Spain and were 1.42 €/m^3.

Time of year and spatial location within the watershed ultimately influence the resource costs (computed from emergy value of chemical potential and geopotential energy) of water. To demonstrate this spatial and temporal variability, a case study is presented using the Foix watershed in northeastern Spain. Throughout the year, the resource value of water varies from 0.21 to 3.17 €/m^3, depending on location within the watershed. It is concluded that FCR would benefit from the evaluation of resource costs using spatially and temporally explicit emergy accounting.

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1. Introduction

At the beginning of the twenty-first century, the Earth, with its diverse and abundant life forms, including over six billion humans, is facing a serious water crisis. All the signs suggest that it is getting worse and will continue to do so, unless corrective actions are taken. Per capita water use is increasing (associated with lifestyle choices) and population is growing. Thus the percentage of water resources appropriated for human use is increasing. Together with spatial and temporal variations in available water, the consequence is that water is becoming increasingly scarce and, where available, quality limitations may arise. The water issue is then a matter of both quantity and quality.

Many suggest (Falkenmark and Rockstroem, 1996; Moss, 2004; Johnson et al., 2001) this crisis is one of water governance, essentially caused by the mismanagement of water (White and Howe, 2004). In fact, the real tragedy in much of the global economy is the effect that water has on the everyday lives of poor people, who are blighted by the burden of water-related disease, living in degraded and often dangerous environments. However, the water situation in developed countries is more about management, quality and allocation of costs than a supply matter; in this sense, governments have started to legislate more carefully on water issues: the European Water Framework Directive is a very good example.

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Nomenclature

CWA	Catalan Water Agency
EU	European Union
EV	economic value
FC	financial cost
FCR	full cost recovery
FV	financial value
IBC	Internal Basins of Catalonia
RC	resource cost
RV	resource value
SC	service cost
WFD	Water Framework Directive
Mathematical variables	
EIMV	emergy intensity of monetary value
Em	emergy (sej)
En	energy (J)
g	gravity (m/s^2)
GEmP	Gross Emergy Product
GDM	Gross Domestic Product
h	altitude (m)
Mcm	million cubic meters (hm^3)
MEmV	marginal emergy value (sej/m^3)
Q	flow (m^3/s)
Tr	transformity
Suscripts	
geo	geopotential
chem	chemical

2. Water Framework Directive

The Water Framework Directive (Directive 2000/60/CE, hereafter WFD)[1] is intended to provide a framework for a common approach to the management of water in all European Union member states. Water is no longer considered exclusively as an unlimited resource, but is dealt with as a basic element of all water ecosystems and essential for sustaining good environmental quality that in turn guarantees the resource. This new perspective is based on promoting sustainable consumption of water within a coherent, effective and transparent legislative framework, with special attention to its use and degradation.

The final objective of the WFD is to achieve a *good status* for all European water bodies[2] by the end of 2015. To do this, the Directive requires a diverse series of actions to be performed: first, types of water bodies are to be identified and classified; second, the development pressures and impacts are to be reviewed and the places where there is a risk of non-compliance with the Directive's objectives need to be identified. Then, agencies must design Programs of Measurements (by means of modifying existing River Basin Management Plans) to reach that ambitious *good status* objective for all water bodies within each basin. The Directive recognizes that both biological and hydro-morphological aspects are important for an integrated diagnosis of quality, in addition to traditionally used physicochemical indicators and measurements of toxic or persistent pollutants.

To sum up, the WFD introduces the following basic principles (EU-WFD, 2000):

- The principle of non-deterioration and achievement of good overall status of surface and groundwater bodies.
- The principle of a combined approach to controlling pollution and the integrated management of the resource.
- The principle of full recovery of the costs associated with water services and the use of aquatic areas.
- The principle of public participation and transparency in water policies.

2.1. Water pricing policies within the WFD

Unnerstall (2007) provides an excellent summary of the WFD, an analysis of its intent from its initial drafts, and interpretation of the costs associated with the full cost recovery (FCR) principle. The Directive states that water pricing policies should be readjusted by 2010 following the guidelines of the FCR Principle. The WFD does not explicitly use the term Full or Integral Cost Recovery (in Article 9 it states "*taking into account the cost recovery principle concerning water*"): the possibility of modulating the principle and of establishing exceptions, as long as they are suitably justified, will surely be part of the policy implementation by 2010.[3] Regarding users, at least industry, households and agriculture should adequately contribute to the recovery of the costs of water services, based on the economic analysis conducted according to WFD and taking account of the *Polluter-Pays Principle*.

2.2. Water "costs"

The WFD clearly states that the concept of cost, is not just costs in the conventional economic sense, but includes "*even the environmental costs and those concerning the resource*". The FCR concept contains diverse terms, which according to the WATECO group guidance document[4] (EU, 2004) include three concepts of cost (summarized in Fig. 1):

Financial costs are defined as operating costs, maintenance cost, capital cost for new investments, depreciation, opportunity costs for capital costs, administrative costs and other direct costs for supplying water or treating wastewater.

Resource costs are defined as the costs of foregone opportunities that other uses suffer due to the depletion of the resource beyond its natural rate of recharge or recovery (for example, the excessive exploitation of underground waters or over use of surface waters).

Environmental costs[5] are defined as the costs of damage that water-uses impose on the environment, ecosystems and those who use the environment (e.g., a reduction in the ecological quality of aquatic ecosystems). It also includes economic externalities such as the loss of employment in the services sector in rural areas due

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[1] At the end of 2000, the European Commission and Parliament approved and published what is known as the Water Framework Directive (2000/60/EC) transposed to a Spanish State law, the text of Water Act 1/2001 of 20 July, modified by Article 129 of Law 62/2003 of 30 December on tax, administrative and social order measures (Spanish Official Gazette no. 313, 31 December 2003).

[2] A water body could be a river (stretch), dam, reservoir, groundwater, lake or transitional coastal waters.

[3] It is of key importance in guiding water pricing policy but does not directly oblige any tax measure to be set up to ensure the cost recovery, which would have required the unanimity of all the Member States.

[4] European Water Economics Working Group (WATECO) has developed some economic guidance documents, in which environmental and resource costs mentioned in the WFD are clearly defined. It is important to remark that great controversies are still associated with those definitions.

[5] We believe that "social costs" is a better term for these costs since they are more associated with the social system and losses associated with those who use the environment, however so as not to confuse the issue we have used "environmental costs' throughout this paper.

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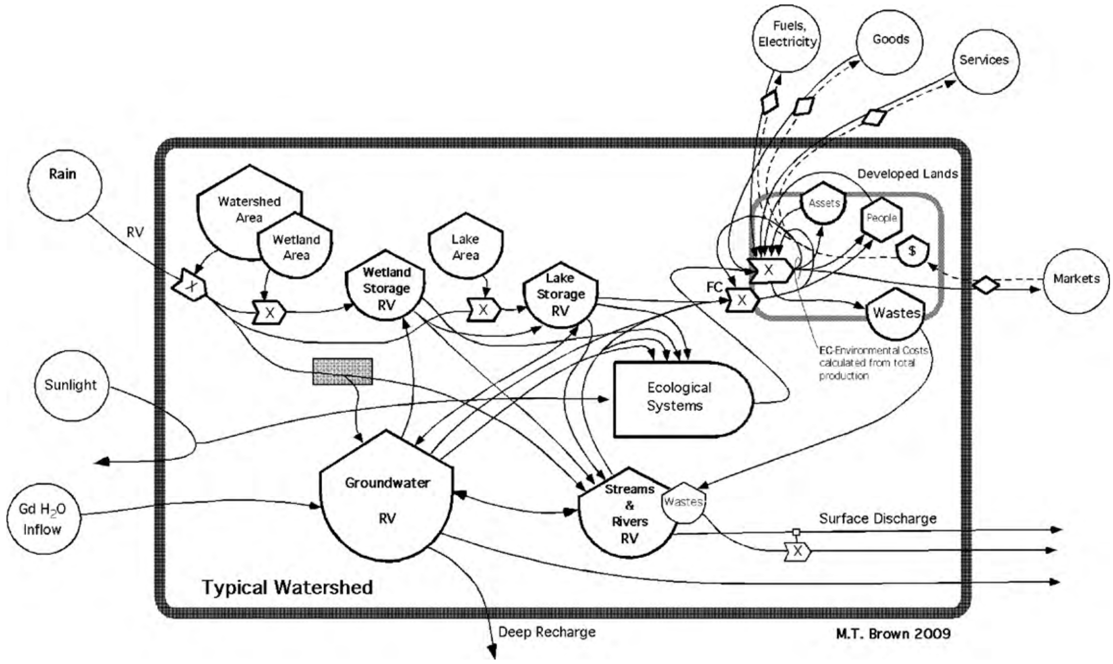

Fig. 1. Systems diagram of a typical watershed showing the various water values. RV, resource value; FV, financial value; EC, environmental costs.

to the social impacts that result from the degradation of the water resources.

The first of these costs can be easily calculated from classical economic accountancy. However, the second and third terms are obviously more difficult to evaluate, at least using current analysis tools within existing water management policies, for several reasons. First, the classifications are not clearly defined which results in mixing environmental values, social costs, and economic costs. Second, they assume perfect markets for water resources and thus perfect substitute-ability of water. Third, traditional economic analysis cannot capture environmental costs related to alteration of physical and biological aspects of water bodies; for as Unnerstall (2007) suggests "there is no market for the cleanness of drinking water". Overall, it appears that the assessment of environmental and resource costs requires the application of a new theoretical and applied approach which could lead to a comprehensive analysis, that details the degradation of not only quality but also quantity. The usefulness of such an approach demands that the definition and calculation procedures of these costs be based on a strong quantitative analysis, but also it should be relatively easy to manage starting from the heterogeneous data available in the EU.

3. Emergy accounting

One such approach is that provided by the emergy accounting methodology. Emergy is defined as the available energy of one kind previously used up directly and indirectly to make a service or product (Odum, 1996). The methods of emergy accounting evolved from the field of "eco-energetics" (Odum, 1971) and its empirical origins stem from the study of the patterns of energy flow that ecosystems and economic systems develop during self-organization (Odum, 1988). The theoretical foundations of emergy are based on the observation that the functioning of all systems, including ecological systems and human social and economic systems, are based on the transformation of available energy. They are fundamentally energy systems exhibiting characteristic designs and organizational patterns that reinforce energy use. Moreover, emergy theory posits that the dynamics and performance of environmental systems can be measured and compared on an objective basis using energy metrics.

In contrast to economic valuation, which assigns value according to utility – or what one gets out of something – and uses willingness-to-pay as its sole measure, emergy offers an opposing view of value where the more energy, time and materials that are invested in something, the greater is its value. Emergy values are most often quantified and expressed as solar energy equivalents, and the unit used to express emergy values is the solar emjoule (sej). By tracking all resource inputs back to the amount of solar energy required to make those inputs, emergy accounts for all the entropy losses required to make a given product, and thereby allows for qualitatively different resources to be considered on a common basis

Emergy synthesis have been used to assess the sustainability of environmental systems of all scales, from economic activity within the biosphere of the Earth (Brown and Ulgiati, 1999), to the sustainability of national economies (Brown et al., 2009; Ulgiati et al., 1994; Lagerberg et al., 1999), to bio-fuel production (Ulgiati, 2001), water supply alternatives (Buenfil, 2001), municipal wastewater treatment (Björklund et al., 2001), water management (Chou and Lee, 2007; Tilley and Brown, 1998, 2006; Cohen and Brown, 2007) and historical comparisons of industrial and pre-industrial agricultural systems (Rydberg and Jansen, 2002).

4. Methods

To calculate emergy of a resource or flow of energy or material, first the quantity is determined in either units of energy (i.e., Joules) or mass (i.e., grams). The amount of input emergy dissipated per unit output available energy is called solar transformity. It represents the emergy investment per unit product. It may therefore be considered a quality factor, identifying the intensity of the biosphere support to the product under study. That *transformity* (ratio of emergy to avalaible energy, sej/J) is used to convert available energy to emergy by multiplying the energy by the transformity. If the flow is evaluated as mass, then it is converted to emergy using a *specific emergy* (ratio of solar emergy to mass; sej/g). Transformities and specific emergies are frequently calculated in separate eval-

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uations. In this paper, transformities and specific emergies were derived from previous evaluations of global processes (see Odum, 2000; Odum et al., 2000).

4.1. Cost definitions using the emergy approach

When the emergy approach is used to determine the cost of water following the WFD guidelines, the three classes of costs are defined in emergy terms, evaluated and converted to monetary equivalents. The difference between emergy accounting and financial cost accounting is that the emergy approach does not rely on markets to impute prices, yet once the emergy values are calculated it is common practice to convert them to monetary units for ease of communication and to incorporate costs within the economic system to support full cost recovery.

Conversion of emergy to currency is accomplished by dividing emergy values by a conversion factor computed from the economy within which the evaluation is being conducted (Odum, 1996). This conversion factor sometimes called "emergy–money ratio" is obtained after computing all the emergy flows supporting a country's economy and dividing that total emergy by the GDP of the country under study. For the purposes of this paper, emergy was converted to Euros using a conversion factor derived from the economy of Spain (the country of focus in the case study that follows). A complete study of the emergy flows in Spain can be found in the online tool developed by Sweeney (online update of the work by Sweeney et al., 2006).

Emergy evaluation of the three classes of water costs requires a systems perspective. Shown in Fig. 1 is a systems diagram of a typical watershed emphasizing the flows and storages of water. The diagram is annotated with *financial value* (FV: the monetary equivalent emergy costs of water and water infrastructure), resource value (RV: from which resource cost can be computed) and environmental value (EV: from which the environmental costs can be computed) to indicate at what point in the system the emergy value of the water resources are calculated. Since there are numerous different water storages within a typical watershed, each one can be evaluated separately and each has different emergy values.

The *financial value* is clearly understood as the costs associated with the provision of water that include costs of water and the water infrastructure. Table 1 lists several sources of water and the emergy and Euro costs of making the water available; the costs do not include delivering the water to the end user. These data were derived from water costs in the USA (Buenfil, 2001). Our assumption is that European systems of water treatment are similar to those in the USA; obviously detailed analysis of treatment costs in Europe should be conducted to better refine these data.

The *resource value* (RV) is computed from the emergy in the water itself, and is determined for each type of water: rain, water stored in wetlands, water stored in lakes, river water, and ground water separately by computing the resource value that is used by a consumer. Thus the resources cost (RC) is computed from the RV and depends on the quantity of water that is used and the water source.

Water has two important resource values. The first is the chemical potential energy in water and is expressed as its purity relative to seawater (at 35 ppt). The chemical potential energy in water within a watershed is computed from the Gibbs free energy of each type of water relative to salt water within evapotranspiring plants or relative to oceans receiving the rain (generally both are assumed to be 35 ppt). The Gibbs free energy of rainfall is equal to 4.94 J/g assuming rain with dissolved solids concentrations of 10 ppb (Odum, 1996) and is calculated as follows:

$$G = \frac{RT}{w} \ln\left(\frac{C_2}{C_1}\right) \qquad (1)$$

where G is the Gibbs free energy, R is the universal gas constant (8.33 J/mole/degree), T is the temperature (300 K), w is the molecular weight of water (18 g/mole), C_1 is the concentration of water in sea water (965,000 ppm), and C_2 is the concentration of water in rain (999,990 ppm).

Each type of water (lakes, wetland water, groundwater, etc.) has differing dissolved solids concentrations and thus they will have slightly different chemical potential energy (En_{water}), obtained after applying Eq. (1) with the corresponding salinities. The emergy of each type of water is computed by multiplying its energy by an appropriate transformity (calculated separately) as follows:

$$Em_{\text{Chem Pot}} = En_{\text{water}} \cdot Tr_{\text{water}} \qquad (2)$$

The emergy is equated to the resource value. Table 2 lists average chemical potential emergy and the resource value in Euros per cubic meter for the different types of water shown in Fig. 1. The footnotes to the table explain the assumptions and provide the computations for energy and emergy.

The second value of water is in its geopotential energy; the work that water running off the landscape can do as it falls from higher elevations to lower elevations. The energy of geopotential is calculated from the product of flow (Q), density of water (ρ), average altitude (h), and gravity (g) as follows:

$$En_{\text{geop}} = Q \cdot \rho \cdot h \cdot g \qquad (3)$$

The emergy of geopotential energy of water is computed by multiplying the geopotetial energy by an average transformity for each elevation (after Odum, 2000) as follows:

$$Em_{\text{geop}} = En_{\text{geop}} \cdot Tr_{\text{geop}} \qquad (4)$$

Table 3 lists examples of the geopotential energy of water at different elevations and the emergy and Euro value per cubic meter. The footnotes to the table explain the assumptions and provide the computations for energy and emergy.

With two separate values of water, chemical potential and geopotential, it is possible to compute the resource values that are used when water is consumed or otherwise depleted in quantity or quality. For instance, if a user takes water at a given elevation in

Table 1
Emergy costs of irrigation and potable water including production costs and assests and infrastructure to produce[a].

Type of water	Human service (E12 sej/m^3)	Fuels & electricity (E12 sej/m^3)	Chemicals & supplies (E12 sej/m^3)	Plant assets (E12 sej/m^3)	Total (E12 sej/m^3)	em€. Spain[b] (2008 em€/m^3)
Irrigation groundwater	0.41	0.25	0.00	0.16	0.82	0.17
Hard surface water	1.63	0.25	1.91	0.41	4.20	0.87
Soft surface water	2.59	0.30	4.90	0.41	8.20	1.71
Aquifer water	1.91	0.54	2.86	0.41	5.71	1.19
Reverse osmosis (brackish gdw)	5.72	1.01	0.54	0.54	7.81	1.63
Reverse osmosis (saltwater)	5.44	3.26	0.27	0.54	9.52	1.98

[a] After Buenfil (2000).
[b] Emergy is converted to Euros using the emergy Euro ratio for Spain (2008) = 4.8E12 sej/€.

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Table 2
Global average chemical potential energy, transformities, emergy and Euro values of several terrestrial water storages.

Note	Item	Chem pot energy	Units	Transformity (sej/unit)	Solar Emergy (E+12 sej/m^3)	Monetary value (2008 em€/m^3)
1	Rain	4.9E+06	J/m^3	31,000	0.15	0.03
3	Wetland water	4.7E+06	J/m^3	43,100	0.20	0.04
4	Lake water	4.9E+06	J/m^4	50,400	0.25	0.05
2	River	4.8E+06	J/m^3	81,000	0.39	0.08
5	Ground water	4.4E+06	J/m^5	191,400	0.85	0.18

[#] Based on 4.8E12 sej/€ in Spain.

Notes: (1) Rain: volume = 1 m^3; density = 1.0E+06 g/m^3; concentration rain 10 ppb = 999,990 ppb water; concentration sea water 35 ppt = 965,000 ppb water; R = 8.33 J/mole/degree; T = 300 K; $w = 18$ g/mole; Gibbs free energy = (Eq. (1)); energy in rain = 1.0 m^3 × 1.0E6 g/m^3 × 4.94 J/g = 4.94E6 J/m^3; transformity = 31,000 (Odum, 2000).

(2) Wetland water: volume of water taken as 89.6% moisture content of volume of peat plus avg. standing water; peat water = 8.96E−01 m^3; Avg. water depth = 2.00E−01 m; Gibbs free energy = 4.94 J/g; volume = 1 m^3; density = 1.0E+06 g/m^3; concentration water 2 ppm 998,000 ppb water; concentraion sea water 35 ppt = 965,000 ppb water; R = 8.33 J/mole/degree; T = 300 K; $w = 18$ g/mole; Gibbs free energy = (Eq. (1)); energy in water = 1.0 m^3 × 1.0E6 g/m^3 × 4.67 J/g = 4.67E+06 J/m^3; transformity: 43,100 (Brown and Bardi, 2001).

(3) Lake water: volume = 1 m^3; density = 1.0E+06 g/m^3; concentration lake 500 ppb = 999,500 ppb water; concentraion sea water 35 ppt = 965,000 ppb water; R = 8.33 J/mole/degree; T = 300 K; $w = 18$ g/mole; Gibbs free energy = (Eq. (1)); energy in lake water = 1.0 m^3 × 1.0E6 g/m^3 × 4.38 J/g = 4.87E+06 J/m^3; transformity = 50,400 (Brandt-Williams, 2002).

(4) River chemical potential: volume = 1 m^3; density = 1.0E+06 g/m^3; concentration river 1 ppm = 999,000 ppb water; concentraion sea water 35 ppt = 965,000 ppb water; R = 8.33 J/mole/degree; T = 300 K; $w = 18$ g/mole; Gibbs free energy = (Eq. (1)); energy in river = 1.0 m^3 × 1.0E6 g/m^3 × 4.81 J/g = 4.81E+06 J/m^3; transformity = 81,000 (Odum, 2000).

(5) Ground water: based on Floridan Aquifer in Florida, USA; volume = 1 m^3; density = 1.0E+06 g/m^3; concentration gd. water 10 ppb = 999,900 ppb water; concentraion sea water 35 ppt = 965,000 ppb water; R = 8.33 J/mole/degree; T = 300 K; $w = 18$ g/mole; Gibbs free energy = (Eq. (1)); energy in water = 1.0 m^3 × 1.0E6 g/m^3 × 4.38 J/g = 4.87E+06 J/m^3; transformity = 191,400 (Brown, unpublished data).

a watershed and only half is returned at the same elevation then the user should pay the value of the lost geopotential work (i.e., the work the water would have done if it had not been removed from the stream or river) as well as the chemical potential value that is no longer available. In like manner, if a user removes some water and returns all of it, but it has lost some of its chemical potential, because it now carries a higher dissolved solids load, then the user should pay the difference in the resource quality calculated as the difference in the chemical potential; yet since all the water is returned, it still has its geopotential.

Evaluating the environmental costs (ECs) as defined by the Directive presents a relatively complex undertaking. First ECs are defined as damages that water-uses impose on the environment, ecosystems and those who use the environment. Second they may also include potential risks, for instance, a water use that may increase the likelihood of a flood. Under this second category it is suggested that a risk premium reflecting insurance costs be included. In our analysis of environmental costs we have chosen to ignore potential risks, recognizing the inherent difficulties of providing a generalized risk factor for water uses. Instead we focus on the actual potential damages.

Using Fig. 1 as a guide, the assumption of environmental costs is that water is a necessary input to the productive processes of any region. Shown in the diagram, total productivity (regional Gross Emergy Product, *GEmP*) measured in emergy, is the sum of inputs from water, environmental systems, and imported energy, goods and services. If a linear relationship between total production and water availability and use is assumed, then the marginal emergy value of water is the *GEmP* divided by quantity of water. While it may be that a linear relationship is not accurate, especially at the extremes, we assume linearity in this analysis. The equation to determine the marginal emergy value of water is as follows:

$$MEmV_{\text{water}} = \frac{GEmP}{Water_{\text{total use}}} \tag{5}$$

where $MEmV_{\text{water}}$ is the marginal emergy value of water in sej/m^3, *GEmP* is the emergy value of regional Gross Domestic Product, $Water_{\text{total use}}$ is the sum of rainfall and groundwater use.

4.2. Converting emergy to monetary equivalents

Conversions of emergy to Euro value are based on the conversion factor of 4.8E12 sej/€ for Spain in 2008 (updated online from Sweeney et al., 2006), the country of focus in the case study that follows. The conversion factor was calculated as follows:

$$EIMV\,(\text{sej/euro}) = \frac{GEmP\,(\text{sej})}{GDP\,(\text{euros})} = \frac{5.76\text{E}24\ \text{sej/yr}}{1.18\text{E}12\ \text{euros/yr}}$$
$$= 4.8\text{E}12\ \text{sej/euro} \tag{6}$$

where *EIMV* is the Emergy Intensity of Monetary Value, *GEmP* is the Gross Emergy Product (total emergy use in economy, 2008), and GDP is the Gross Domestic Product (2008).

5. Case study: Foix watershed

Foix watershed is a relatively small basin (301.3 km^2) located in the northeast of Tarragona province, Spain. The river originates in a mountainous area named Sierra de la Llacuna and flows to the sea forming a small delta at Cubelles beach, in Barcelona province. Its

Table 3
Global average geopotential energy, transformities, emergy and Euro value of water at different elevations.

Elevation (m)	Energy[a] (J/m^3)	Transformity[b] (sej/J)	Emergy (E12 sej/m^3)	Monetary value[c] (2008 em€/m^3)
Surface	4.31E+06	34,381	0.15	0.03
990	9.70E+06	37,178	0.36	0.08
1950	1.91E+07	35,354	0.68	0.14
3010	2.95E+07	50,370	1.49	0.31
4200	4.12E+07	59,484	2.45	0.51
5570	5.46E+07	130,122	7.10	1.48
7180	7.04E+07	187,376	13.18	2.75

[a] According to Eq. (3).
[b] After Odum (2000).
[c] Based on 4.8E12 sej/€ in Spain.

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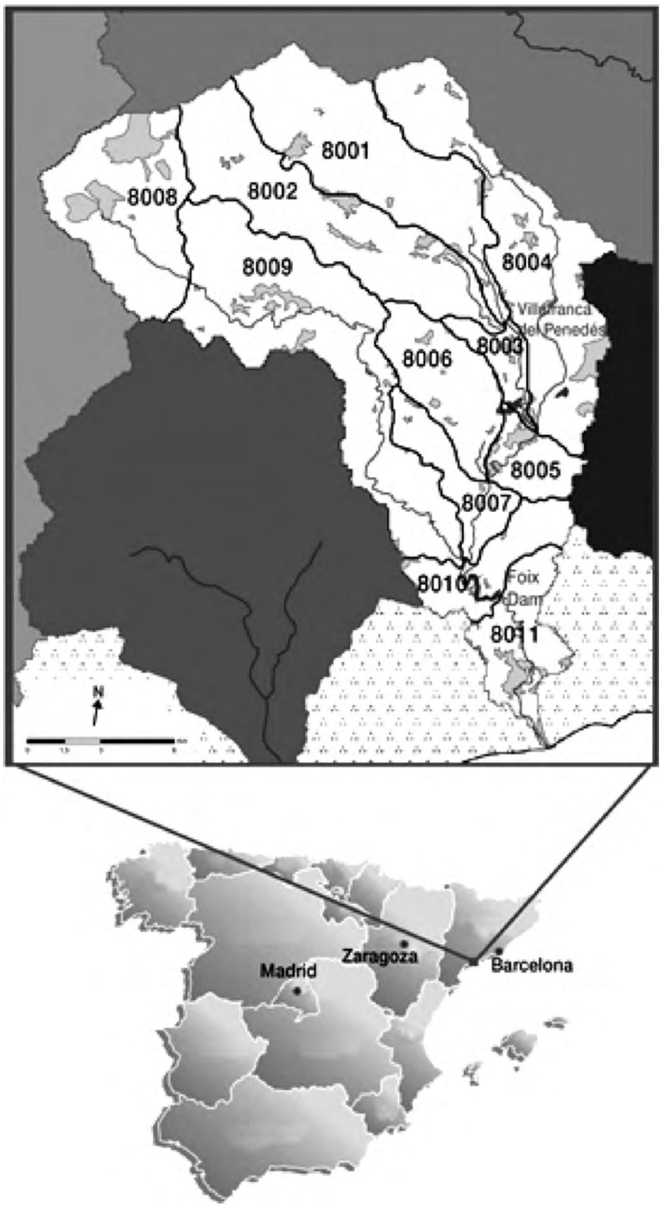

Fig. 2. The Foix watershed, showing eleven sub-basins used in the spatial and temporal emergy evaluation of resource values of water. Urban areas are indentified in grey and industrial areas in black.

total length is 163.8 km, and has three main tributaries: Marmellar, Pontons and Llitrá. Fig. 2 shows a map of the Foix River Basin, including its partition into eleven sub-basins (CWA, 2005a). There are four main water courses within the watershed: the main channel is the Foix River, comprised of the reaches in sub-basins 8001, 8003, 8005, 8007, 8010 and 8011; the Pontons tributary (sub-basins 8002) is located on the left side of the main Foix channel, as well as the Marmelar, on the western side of the watershed, which contains sub-basins 8008 and 8009 and joins to the main course before the Foix. Finally, the Llitra headwater is formed by area 8004, in the eastern part of the watershed.

There is a Dam in the area close to Castellet i la Gornal which retains most of the water flowing into it. The Foix Dam is devoted to water storage, not to electricity production, as is characteristic of many others Dams in the Internal Basins of Catalonia. The quality of the stored water is very low, which resulted in the closing of the fishery within the reservoir several times during 2009.

Average annual rainfall in the basin of 182 million m^3 (i.e., 182 hm^3 or 586 mm) results in average annual flow of the river of only 9.47 Mcm, corresponding to an average flow of 0.3 m^3/s (CWA, 2004). The Foix flow regime is typical for Mediterranean rivers, characterized by carrying little water volume through out the year, except in torrential rainfall episodes, mainly in autumn. Rainfall is clearly insufficient for current agricultural and urban demands and thus these demands are often met with groundwater throughout the year. In spite of this shortage, torrential episodes happen in the area, although most of the water cannot be collected.

Increasing mean annual temperature and the progressive decrease of the relative humidity inland and at higher elevations, tend to increase evapotranspiration and, as a consequence, the available water volume for the aquifer recharge. The overall annual water deficit is about 5 million m^3 per year (García i Ruiz, 1997).

Populations are not evenly distributed through out the basin since there has been a progressive depopulation of the inland mountain range which has been compensated for by a population increase in the coast area. The basin's permanent population is about 100,000 inhabitants, within about 15 important villages, but with a very high population variation, almost doubling, due to the numerous visitors during the summer vacation period. A significant number of people travel to the basin from Barcelona and its metropolitan area creating a massive urban exodus that coincides with the summer minimum hydrological availability period.

Because of the limited availability of water in origin, there exist an important amount of subterranean catchments within the Foix watershed. In fact, the mentioned urbanizations have been traditionally supplied by deep, through extractions close to them. The depth and amount of those water abstractions have increased as the demands multiplied. However, these solutions do not completely solve the problem (Martínez, 2009).

5.1. *Case study methods*

5.1.1. *Estimating surface water resources*

The management of water quality requires inter-disciplinary decisions that need to be based on responses of water quality to changing controls (McIntyre and Wheater, 2004). The relationships among waste loads from different sources and the resulting water qualities of the receiving waters are best described with mathematical models.

Since only two of the sub-basins contained monitoring and control stations for quality data and four sub-basins had stations for water flow (CWA, 2006, 2008), it was necessary to use a modeling approach to represent the river basin as a whole. Qual2kw, a well-know surface-water quality model developed by the United States Environmental Protection Agency –US EPA– (Pelletier and Chapra, 2004), was used to simulate the watershed. The model was populated with rainfall, ET, the digital land model of the area, data from the monitoring and control stations, as well as with the diverse input and outputs flow along the stream, including both point and diffuse sources. Then, the model was ran to obtain average discharge data for each of the sub-basins.

5.1.2. *Evaluation of financial value of Foix Water Resources*

The financial value from which financial cost was calculated for the Foix Basin was based on averages of current cost of water using a weighted average of current costs to provide water for urban (24%), industry (22%), livestock (2%), and irrigation (52%)[6] extracted

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[6] It includes the categorisation and definition of water masses (unit of management to be governed by the Programme of Measures for compliance with the WFD objectives), and the risk of non-compliance with WFD objectives in Catalonia. It also responds to the Article 5 (economic analysis that includes an assessment of the current costs of water-related services) of the Directive.

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Table 4
Resource value of chemical potential of water discharge in the Foix basin by sub-basin (January).

Sub-basin	Rainfall[1] (mm/mo)	Energy rain[2] (J/mo)	Trans-formity[3] (sej/J)	Emergy rain[4] (sej/mo)	Discharge[5] (m^3/mo)	Discharge emergy[6] (sej/m^3)	Monetary value[7] (2008 em€/m^3)
8001	72.65	1.53E+13	31,000	4.75E+17	1.61E+05	2.95E+12	0.62
8002	72.81	1.55E+13	31,000	4.79E+17	1.61E+05	2.98E+12	0.62
8003	79.20	3.62E+13	31,000	1.12E+18	3.75E+05	2.99E+12	0.62
8004	76.13	1.86E+13	31,000	5.76E+17	1.61E+05	3.58E+12	0.75
8005	81.25	6.06E+13	31,000	1.88E+18	5.62E+05	3.34E+12	0.70
8006	80.43	7.84E+12	31,000	2.43E+17	8.04E+04	3.03E+12	0.63
8007	81.18	1.12E+14	31,000	3.47E+18	1.10E+06	3.16E+12	0.66
8008	70.53	1.23E+13	31,000	3.82E+17	1.34E+05	2.85E+12	0.59
8009	75.57	3.58E+13	31,000	1.11E+18	3.75E+05	2.96E+12	0.62
8010	81.07	1.17E+14	31,000	3.64E+18	1.15E+06	3.16E+12	0.66
8011	80.94	1.24E+14	31,000	3.85E+18	1.21E+06	3.19E+12	0.66

(1) Data from CWA (2006).
(2) Rain chemical potential energy: volume = rainfall times catchment area; density = 1.0E+06 g/m^3; concentration rain 10 ppb = 999,990 ppb water; concentraion sea water 35 ppt = 965,000 ppb water; R = 8.33 J/mole/degree; T = 300 K; $w = 18$ g/mole; Gibbs free energy = (Eq. (1)); chem. pot. energy in rain = Gibbs free energy × volume.
(3) Transformity = 31,000 (Odum, 2000).
(4) Emergy in rain: emergy (sej) = energy × transformity.
(5) Data from CWA (2004).
(6) Discharge emergy: emergy (sej/m^3) = emergy in rain (sej)/discharge (m^3).
(7) Monetary value: em€/m^3 = discharge emergy/4.8E12 sej/€.

from the IMPRESS report (CWA, 2005b). This document summarizes the delimitation of Catalona's water bodies as well as their pressures, impacts and possible risks of noncompliance with the WFD's requirements.

5.1.3. *Emergy evaluation of the resource value of Foix Water Resources*

Evaluation of the resource value of surface water was undertaken in two parts, first the chemical potential energy (water quality) was evaluated and then the geopotential energy (water quantity) was evaluated. Together these comprise the resource value from which resource costs were computed. Since there is significant spatial and temporal variability to the water resources, we used a GIS based method to evaluate water resources by basin and for each month of the year.

Most of the data needed for the emergy evaluation of resource value (flows, rainfall, evapotranspiration, etc.) were taken from diverse reports provided by the CWA (CWA, 2005a,b, 2006, 2008). Detailed information about land uses was taken from the CORINE[7] application, in order to use uniform European data sets for the analysis.

5.1.4. *Environmental value of Foix Water Resources*

We evaluated the environmental value resources at the scale of the country since data on the Gross Regional Product for the Foix Basin were not available and assuming that the development capacity of the watershed is similar to that of Spain as a whole. We use the total available water that includes both rainfall and groundwater use in Spain for the year 2008 and the GDP of Spain for the same year in Eq. (5). The rational is that all the rainfall is utilized in regional production either directly as irrigation or urban supply, or indirectly through production of resources like soils, forests, or fisheries that humans may benefit from through their harvest. The environmental value calculated in this manner corresponds to the concept of environment cost as enunciated in the Water Directive.

5.2. *Case study results*

5.2.1. *Financial costs of Foix Water Resources*

Our estimates of the annual financial costs to provide water for all sectors of the economy in the Foix basin was 5.2 million €/year, and total water use was 9.7 million m^3. It was estimated from the figures provided by the Catalan Water Agency for the Foix-Gaia-Francolí aggregated area (CWA, 2005b, 2006). Thus the average cost was 0.54 €/m^3 which compares well with the average global values for surface and aquifer water in Table 1.

5.2.2. *Resource value of Foix Water Resources*

The resource values were computed on a monthly basis for each of the sub-basins of the Foix watershed. Tables 4 and 5 list the chemical potential and geopotential resource values for each of the basins in the Foix watershed emergy, using January as an example. The tables show both the emergy values and the monetary value per cubic meter of water. For the month of January, the monetary value of chemical potential emergy in water varied between 0.62 and 0.75 €/m^3, while the monetary value of geopotential emergy was between 0.01 and 0.04 €/m^3. Obviously in the Foix basin, the chemical potential of water is the most important. Sub-basins with the highest relief (8001, 8002, 8008 and 8009) had the highest monetary value of geopotential.

Graphed in Fig. 3 are the monthly emergy values of geopotential and chemical potential for the sub-basins of the Foix watershed. The highest chemical potential and geopotential emergy was during the winter months (highest rainfall months, as to be expected), yet there is an increase in chemical potential emergy in late summer that is not reflected in the geopotential. Presumably because evapotranspiration is highest during that period of the year and therefore there is less total runoff. Geopotential is the lowest during the dry season, however the chemical potential while lower than winter months, exhibits an increase during the dry season.

Monetary value of total resource emergy (sum of chemical potential and geopotential) per cubic meter of discharge is graphed in Fig. 4 for all sub-basins in the Foix watershed. It is most interesting to note that the highest monetary values per cubic meter of discharge occur in the driest months when discharges are lowest. Rain input per stream discharge is highest during these low flow months which generates the highest emergy and monetary values. For the majority of the year resource values are relatively consistent between basins, varying somewhat during the dry sea-

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[7] CORINE (Coordination of information on the environment) is a European programme initiated in 1985 by the European Commission, aimed at gathering information relating to the environment on certain priority topics for the European Union (air, water, soil, land cover, coastal erosion, biotopes, etc.). Since 1994, the European Environment Agency (EEA) integrated CORINE in its work programme. EEA is responsible for providing objective, timely and targeted information on Europe's environment.

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Table 5
Resource value of geopotential potential of water discharge in the Foix Basin by sub-basin (January).

Hidrologic unit	Height[a] (m)	Discharge[b] (m^3/month)	Geopotential energy[c] (J/month)	Transformity[d]	Geopotential energy[e] (seJ/month)	Monetary value[f] (2008 em€)	Monetary value[g] (2008 em€/m^3)
8001	500.9	1.61E+05	7.89E+11	34,300	2.71E+16	5.65E+03	0.04
8002	586.4	1.61E+05	9.24E+11	34,300	3.17E+16	6.61E+03	0.04
8003	168.9	3.75E+05	6.21E+11	34,300	2.13E+16	4.45E+03	0.01
8004	347.3	1.61E+05	5.47E+11	34,300	1.88E+16	3.92E+03	0.02
8005	155.1	5.62E+05	8.55E+11	34,300	2.94E+16	6.12E+03	0.01
8006	202.9	8.04E+04	1.60E+11	34,300	5.49E+15	1.14E+03	0.01
8007	155.1	1.10E+06	1.67E+12	34,300	5.74E+16	1.20E+04	0.01
8008	588.8	1.34E+05	7.73E+11	34,300	2.65E+16	5.53E+03	0.04
8009	588.8	3.75E+05	2.16E+12	34,300	7.43E+16	1.55E+04	0.04
8010	102.1	1.15E+06	1.15E+12	34,300	3.96E+16	8.25E+03	0.01
8011	101.1	1.21E+06	1.19E+12	34,300	4.10E+16	8.55E+03	0.01

[a] Average height of sub-basin. Data from Martínez (2009).
[b] Data from CWA (2004).
[c] According to Eq. (3).
[d] From Odum (2000).
[e] Geopotential emergy = energy × transformity.
[f] Monetaray value = geopotential emergy/4.8E12 sej/€.
[g] Monetary value per m^3 = monetary value/discharge.

son. On the average, during the majority of the year (January to April and October to December) monetary resource value is about 0.50 €/m^3, while it averages 1.62 €/m^3 the four rainy months (May–September).

5.2.3. *Environmental value of Foix Water Resources*

Total water resource use in Spain was 8.4E11 m^3 from rainfall (Sweeney et al., 2006) and 7.8E9 m^3 from groundwater (FAO, 2009) for a total of 8.5E11 m^3/year. Spain's *GEmP* in 2008 was 4.55E24 sej

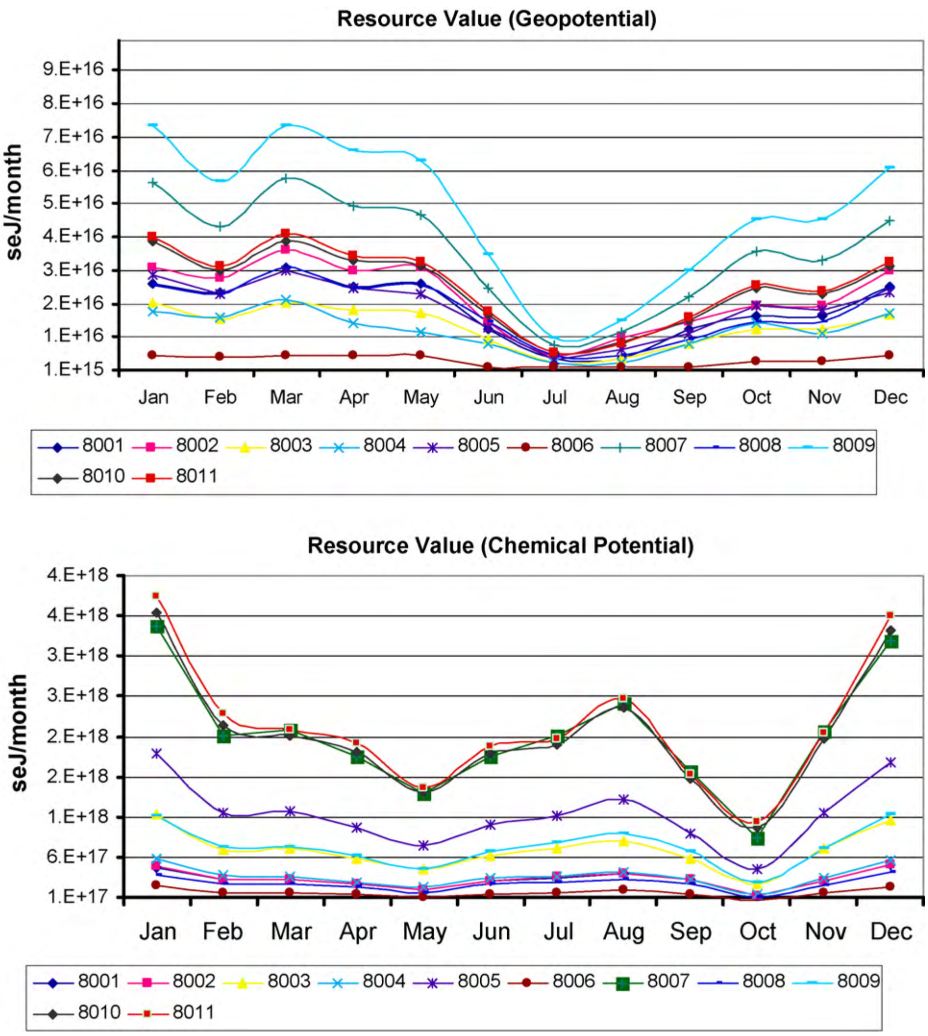

Fig. 3. Emergy resource value per month in the Foix River Basin. (a) Geopotential emergy and (b) chemical emergy.

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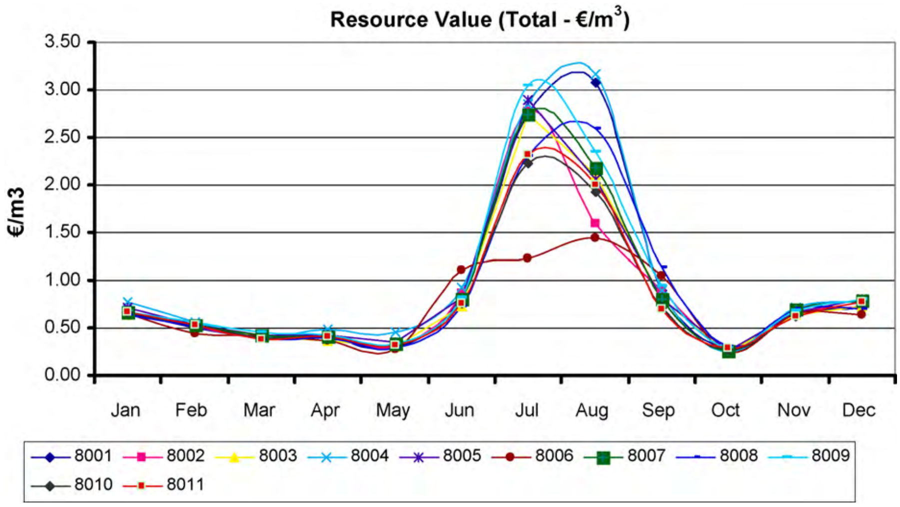

Fig. 4. Total resource value expressed in Euros per cubic meter.

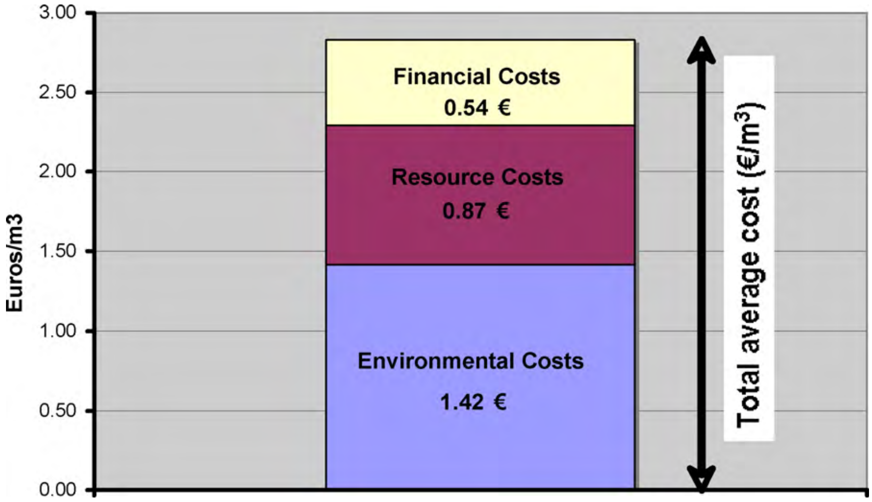

Fig. 5. Contributions to total average water costs in the Foix watershed.

(Sweeney et al., 2006). Using Eq. (5) the marginal emergy value of water resources in Spain was follows:

$$MEmV_{\text{water}} = \frac{5.76\text{E}24\,\text{sej}}{8.5\text{E}11\,\text{m}^3} = 6.8\text{E}12\,\text{sej/m}^3 \qquad (7)$$

Euro equivalent of the emergy value of Foix water, which we define as the average environmental value from which environmental cost (EC) of water may be computed, was obtained by dividing the marginal emergy value of water (Eq. (7)) by the EIMV (Eq. (5)) for the economy of Spain as follows:

$$\text{EC} = \frac{6.8\text{E}12\,\text{sej/m}^3}{4.8\text{E}12\,\text{sej/euro}} = 1.42\ \text{euros/m}^3 \qquad (9)$$

5.2.4. Summary: full cost recovery of Foix Water Resources

Full cost recovery on a volume basis was computed as the sum the three monetary values (financial, resource and environmental) and average values are shown in Fig. 5. The financial costs of water resources were estimated to be 0.54 €/m^3. The resource values, from which costs can be inferred were between 0.21 and 3.17 €/m^3 depending on time of year and sub-basin. Overall, average resource value of Foix water, across all sub-basins and all periods of the year, was 0.87 €/m^3. The environmental costs (based on the marginal emergy value) was 1.42 €/m^3. Overall, the total average costs were 2.83 €/m^3.

While each of these costs varies depending on source, geography, climate, and to some extent economic system, the method of determining values from which costs are computed can be applied to any river system with similar results.

6. Concluding remarks

Several things must be taken into consideration before applying a fixed number based on an average value of water resources. First, to recover full costs for a cubic meter of water assumes that all of the water was taken out of the system and not returned, for instance water that is used for irrigation and is evapotranspired or cooling water that is evaporated. If some water is returned, then only that portion that was used would be charged. Obviously if the portion returned was polluted beyond use, then full cost recovery would be in order. Second using the same reasoning if water is "borrowed" for some time, used in some process and returned unaltered (highly unlikely) then there would be no charge. If all the water is returned however in a more polluted state, using the chemical potential equations give above, it is possible to determine quantity of chemical potential that has been used up. Third, using averages while easy to apply misses the fact that not all water is created equal, both in time and in space. For instance in the Foix watershed, the resource value of water varies over one order of magnitude

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(0.21–3.17 €/m^3) throughout the year and from one watershed to the next.

The case study of the Foix watershed evaluates only the surface water supplies. Similar methods can apply to groundwaters. Note in Table 2 that the chemical potential emergy of aquifer water, on average, is about 6 times the chemical potential in rain water. Thus, it might be assumed that the resource values for aquifer water within the Foix watershed would be significantly higher than these surface water values. To determine the actual value of groundwater in the Foix watershed would require a more detailed study of groundwater dynamics within the basin.

Correct implementation of the concepts and regulations established by the WFD involves a complex structure of initiatives that will provide the necessary tools and proper criteria for new water management policies. These policies are to be based on sustainability criteria from a perspective of the environment, economy, maintenance of water resources, and complete transparency. In addition, without a doubt, the demand for tax collections that will ensure total cost recovery will require the WFD to set out, in a clear way, a method to calculate the environmental costs and those of the resource no easy task using traditional economic analysis. The approach outlined and demonstrated in this paper may be of value in setting up a program of full cost accounting that could then lead to recovering the truer costs of water, but more importantly a program of incentives to maintain and protect water resources.

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