Integration of hydrological and economic approaches to water and land management in Mediterranean climates: an initial case study in agriculture

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Abstract

A distinction is commonly drawn in Hydrology between 'green' and 'blue water' in accounting for total water availability in semi-arid regions. The criterion underlying this classification is important for successful water management, because it reveals how much natural water is and/or could be used by households, industry and, especially, agriculture. The relative share of green and blue water is generally treated as a constant. In recent years, a growing hydro-geological literature has focused on a phenomenon that significantly affects the stability of the green/blue water ratio. This is the increase in land cover density and its impact on runoff in regions with a Mediterranean climate, such as the Ebro Basin in Spain. We seek to carry this knowledge over into the parameters of disciplines concerned with the economic valuation of water and territorial resources, and translate it into the language used by water management professionals in the expectation that this contribution will improve the way we assess and account for real water availability. The heart of the matter is that the increasing density of forest cover produces both positive and negative environmental and economic impacts, presenting new economic and environmental problems that must be examined and assessed in a hydrological-economic context. We will show that these positive and negative effects are sufficiently important to merit attention, whether they are measured in physical or economic terms. Finally, we make an initial proposal for the economic valuation of some of the effects produced by these hydrological changes.

Additional key words: blue water; green water; hydro-economic framework; water resources accounting.

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Abbreviations used: CWC (crop water consumption); CWR (crop water requirements); DNM (differential net margin); ETc (crop evapotranspiration); ETo (benchmark evapotranspiration); RO (runoff coefficients); TNM (total net margin).

Introduction

Water is different from other scarce resources. As Hanemann (2006) argues, the valuation of one cubic meter of water depends on place, time and variability or quality. Another key feature is 'mobility': water differs from other resources because it can take different forms (surface and underground water, evaporated water and so forth) and its uses are sequential. A single water molecule is typically used many times as it moves downstream. This potential reusability is an important consideration for water accounting and management, and it is especially relevant when the resource is scarce, as is the case in Mediterranean climate regions, and is a cause of increasing concern given the direction of certain climate change predictions. In this light, the concept of water availability must take into account all the possible reutilizations, whether natural or man-made.

Our main aim in this paper is to outline an integrated economic and hydrological framework to examine the positive and negative impacts caused by the spontaneous land cover dynamic affecting water availability. As a first step to illustrate this approach we shall estimate the economic losses in irrigated agriculture caused by the increase in woodland vegetation in a specific location and period.

First, however, it may be appropriate briefly to explain our motivation. According to recent hydrologic literature, a process of re-vegetation has been in progress since the middle of the 20th century (Lopez Moreno *et al*., 2008, 2010) following the abandonment of farms in the water catchment areas of the Ebro Basin (northeastern part of Spain). In short, these papers suggest that the sharp decline in animal husbandry, farming and forestry has allowed a sort of 'sponge' to develop, which absorbs a considerable part of the rainfall received. As we will explain later in more detail, this process has affected the volume of water available in water courses, due to the growing needs of new vegetation. Ceballos *et al*. (2008) find a similar situation in the nearby Duero Basin. In the same vein, although for different reasons, Hoff (2006) on a global scale, and Tague and Dugger (2010) for the Southwestern United States, explain how different land uses upstream can dramatically alter the hydrological equilibrium downstream. All of these contributions stem from recent developments in the hydrologic literature on forest-water interactions such as Zhang *et al*. (2001), Andreassian (2004) or Sun *et al*. (2006).

The concepts of green and blue water defined in Falkenmark (2003) are important in this case because they provide a basis to revisit water management and accounting. Green water is that part of precipitation which is initially found in the area of unsaturated ground and therefore does not filter into aquifers or form part of surface run-off, and bluewater is the part that directly or indirectly ends up as surface flows. Meanwhile, one of the basic tenets of the somewhat later concept of integrated water and land management is the complete interdependence of land cover, climate and agriculture as argued in Falkenmark and Rockström (2006).

Traditional hydrological planning and management were based on extensive efforts to ensure a supply of blue water to irrigated areas and urban settlements via reservoirs and a complex network of canals. However, we now know that this is only one of the possible strategies that could be applied. In particular, we should not consider the run-off-rainfall ratio as a constant when it comes to water management grounds.

In this context, careful assessment will be needed of all the environmental outcomes that every reallocation might imply, whether due to natural or socio-economic causes. This means we must consider a wider framework in which we can depict the constraints and side effects associated with the specific problem raised.

Our first objective, then, is to outline an integrated economic and hydrological framework to examine the positive and negative impacts caused by the spontaneous land cover dynamic affecting water availability in line with long-standing proposals made by scholars such as Rosegrant *et al*. (2000) and Cai *et al*. (2003), and more recently by Ward *et al*. (2006), Heinz *et al*. (2007), and Mainuddin *et al*. (2007). We are aware that this means treading a fine line between the natural and the social sciences, but we believe this is the only way forward for researchers interested in natural resources management problems. We are convinced there is knowledge to be transferred from the natural to the social sciences, in particular in the fields of water, forest and land management.

To illustrate this general framework we describe and analyze a specific case: the value of the 'blue' water used in agriculture that could be 'recovered' from a reduction in land cover density in a sub-region of the Ebro basin, namely, the province of Huesca. In short, the specific problem we wish to highlight is that more green water is captured by the re-growth of vegetation following the abandonment of land, and less blue water remains available for human use. This analysis requires a precise knowledge of green and blue water consumed by crops, and thus the productivity and benefits currently yielded by each cubic hectometer of green and blue water, as well as an accurate picture of the hydrological balance in terms of the origins and causes of observed annual water flows.

Material and methods

Conceptual framework: general outline

A partial approach to this complex issue may lead to simplistic, not to say hazardous conclusions, making it necessary to focus on the problem from numerous different angles in order to ensure it is addressed as widely as possible. From an environmental standpoint, land cover in semi-arid climates plays a key role in preventing the degradation of the soil and desertification, and in developing and maintaining the optimum biotic capacity of the substrate (Cohen *et al*., 2006), as well as its ability to store carbon (Schlesinger and Andrews, 2000). Furthermore, there is a trade-off between biodiversity and economic returns which is well established in Polasky *et al*. (2008).

Despite the enormously important environmental role of vegetation, we focus on the increasing growth of scrubland cover density rather than on protection of the soil, a function that is assumed to be performed by the existing forest. This density is the result of a sudden change away from the practices of generations in the use of woodland and meadows by the local inhabitants.

It could be argued against the general backdrop of climate change that an excess of shrub cover represents a natural carbon sink. Some studies have suggested a correlation between hydrological cycles and the role of vegetation in carbon storage (Nemani *et al*., 2002) and, indeed, woodland in the province of Huesca alone provides a sink for over 9.5 metric tons of CO_2 (Notivol, 2009). However, a number of scientific papers published in recent years show a certain positive correlation between the rise in the concentration of CO_2 in the atmosphere and the proliferation of woodland vegetation, as if the phenomenon acted as a ‘feed’, driving forest growth and feeding back into the process (Oren *et al*., 2001). Nevertheless, most studies conclude that these changes in land use affect the size of the CO_2 flow between plants and the atmosphere (Houghton, 2003).

Meanwhile, carbon storage in crops and plantation forest are considered a ‘temporary’ stock by the Kyoto Protocol, meaning they absorb CO_2 from the atmosphere but it is then released again when the plants are consumed. With a view to the post-Kyoto period, however, the United Nations (UN-REDD program) has suggested using forests as permanent carbon sinks, questioning their use for temporary storage as has been the case to date. The initial logic behind this reasoning is to make use of existing stocks, even if they are not new. Second, if timber from sustainably managed woodland is used to produce durable goods, the carbon will remain in stock, but it will not if the wood is burned.

Numerous cost-benefit studies of the way the soil and vegetation function as a carbon sink have been published. For example, Muys *et al*. (2003) analyzed different types of woodland and farm crops in Belgium and in tropical forests. Meanwhile, Lubowski *et al*. (2006) performed an econometric estimate of the value of different land uses (crops, forest, pasture and urban use) as carbon sinks.

A further significant matter is the problem of energy supply and the diversification. The advantage of using biomass for the production of energy is that it allows diversification of the energy mix and reduces local consumption of much more harmful fossil fuels. It is now some time since Hall and House (1994) first addressed the dilemma presented by the net balance of forest CO_2 storage and the use of biomass to generate power. The conclusion of the subsequent literature on this topic is, as might be expected, that it all depends on the amount of energy required to make use of biomass. In any case, we are referring to energy generated by excess biomass rather than to a shift from forest to agricultural uses, as is the case in Fargione *et al*. (2008).

The literature also contains a number of economic studies concerned with other aspects of the problems raised by forest vegetation in the Pyrenees, such as the risk and control of fire (Riera and Mogas, 2004), land cover, and soil erosion (Riera *et al*., 2007). It now seems clear that cover density is connected with the seriousness and spread of periodic wildfires. Enormous public resources have had to be mobilized over the last decade to prevent and, especially, to extinguish large fires.

The dilemma, then, is whether it is more efficient from an economic and environmental standpoint (i) to allow the current evolution of land cover as a temporary carbon sink, an aid to the control of erosion and a platform for biodiversity, which would imply allowing green water consumption to continue on its present path and accepting the fire risk; or (ii) to take action to reduce the density of land cover, which would increase the blue water run-off and could generate additional benefits, for example in the area of energy production (hydroelectricity and biomass) and the availability of more water for agriculture. This second option would of course be subject to environmental restrictions at all times, to ensure biodiversity and the preservation of a fertile area for reasons of erosion control. Our task, then, is to provide a sound basis of information and reasoning to decide whether to maintain the *status quo* or adopt a different approach to the management of forest land.

As explained above, the complexity of the combined management of water and land resources involves several disciplines, and so the action or inaction of one sphere often interacts with the others, not to mention the benefits obtained or harm caused.

To take this a little further (see Figure 1), active forest management to reduce the density of land cover would achieve an increase in run-off, implying the availability of more water for crops downstream and for hydroelectric generating, and at the same time allowing energy and livestock uses of biomass and providing timber. This would both reduce dependence on fossil fuels in the Spanish energy mix and generate income for the local population. Net carbon emissions balance may be uncertain (storage *vs.* reduction in emissions), but should be taken into account. Finally, such management would reduce the area afflicted by fire, mitigating economic losses and adverse environmental outcomes. The main constraints on forest management of this kind would be set by the initial scope of crop and biodiversity objectives established for each district.

The above outline is similar to, though broader than, that proposed by Baskent and Kucuker (2010) with reference to the joint management of water, timber and carbon.

Clearly, a complete evaluation of the proposed outline would require a full program of research that is beyond the scope of this paper. To begin, then, we focus on just one of the issues mentioned. The aim is to assess the increases in the availability of irrigation water that could be obtained by partially reversing the dynamic explained in the preceding section. This is discussed in the next sections.

Methodology: the economic value of irrigation water

The economic value of water is a wide-ranging, complex issue. Numerous economic techniques may be used to value water resources, based on market and non-market, direct or indirect valuations, (hedonic price methods, market-based transactions, derived demand functions, random utility models, travel cost method, damage avoidance costs, contingent valuation and so on [see Chapter 4 of Azqueta (2007) for a general explanation of these methods, and Turner *et al*. (2004), or Annex III of Brouwer *et al*. (2010) for details of their application in the case of water]. Market information

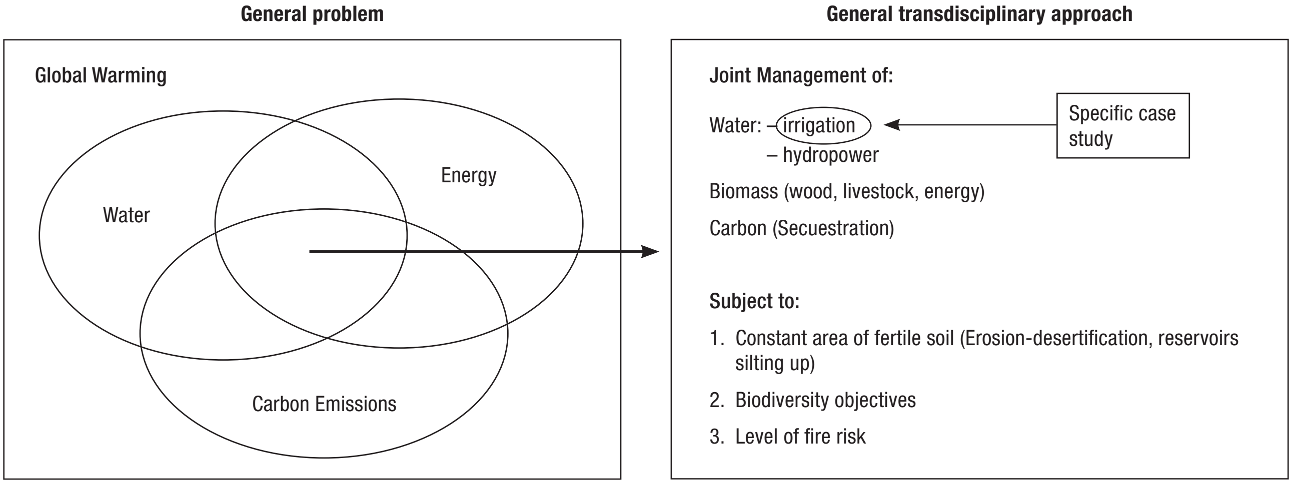

Figure 1. General and specific approaches.

is generally easily available (in official statistics, etc.). However, studies of the value of water used in agriculture usually adopt a narrow perspective for reasons of practicality, focusing on variations in water use and specific measures (*e.g.* surface water, yield, and evapotranspiration) in quantities that would not affect the stability of ecosystems, while excluding other possible uses or values.

Various methodologies can be used to value blue water and estimate the effects of any increase in its availability, in this case by reducing wild land cover. However, it will be necessary to find a way to estimate farmers' gains from each additional unit of water, as the producer's surplus and productivity curves are not directly observable.

In general terms, water 'prices' may be set either by the free market or regulated, as they are in Spain and, indeed, in most of the world's countries. If individual water buyers are free to adjust use to meet their needs at the specified price, then statistical analysis of data on the relationship between water consumption and price will provide a measure of the economic value of water to the end user. For this method to work, however, historical regulated prices must vary over time and water buyers must be free to adjust demand to price changes. For example, the method will not work if water users are constrained by a ceiling on maximum water use, or if water use is not allowed to increase when prices fall. Furthermore, the value obtained needs adjustment to reflect the costs of water transportation, storage and treatment for it to be comparable to instream raw water values. As is well known, regulated water prices in Spain barely reflect the cost of providing water, let alone the marginal value of each unit of water to the farmer.

The recent literature provides solutions to these difficulties. Novo *et al*. (2009) define the economic value of blue water in terms of shadow prices or scarcity values. The present study uses data from different sources about such water shadow prices in the Ebro Basin depending on the degree of scarcity ranging from € 0.01 m^{-3} (no scarcity) to € 0.15 m^{-3} (high scarcity). The shadow price refers to farmers' willingness to pay for an extra unit of water for irrigation, and it is equivalent to the marginal value of available water endowments, measuring the benefits derived from an increase in water availability.

Ashfaq *et al*. (2005) proposed a methodology to evaluate the economic value of water employing the 'residual imputation' method, which is based on net increases in income resulting from water added in production processes. Similarly, Ward and Michelsen (2002) presented a valuation based on the change in net income. We too propose a valuation based on net income variations, which we estimate by comparing irrigated and unirrigated farming. This approach has the advantage that it does not need much information, and the statistical data on output and income from irrigated and unirrigated farming provided by the Spanish Ministry of Agriculture is sufficient for the purpose. The Ministry data base is in fact our main source of information, providing two measures of irrigation water values: total net margin per cubic meter and differential (irrigated minus unirrigated) net margin per cubic meter.

We may also draw on the work of Bos (1997), who designed an index for "Harvesting *vs*. Applied Water" and analyzed productivity in terms of water distributed to the crop. Lorite *et al*. (2004a,b and 2007), Gil *et al*. (2009), Lorite and Arriaza (2009) and Carrasco *et al*. (2010) described the calculation of irrigation water productivity (in kg m^{-3}) of irrigation applied. These authors also treated the increase in the value of output due to irrigation as the difference between the irrigated crop yield minus the same crop yield on unirrigated land at market prices, following a procedure similar to that defined in Rodríguez Casado *et al*. (2008) and Novo *et al*. (2009). We refer to this as 'differential net margin' in the following sections. The residual value method is also a technique applied to valuate water used as an intermediate input to production, when assigning appropriate prices to all inputs but one. Thus, the not accounted value of product is attributed to the residual input, *i.e.,* water [see Young (2005), for a review of the use of this technique, and Berbel *et al*. (2011), for an application in Spain].

In the results, we will see that the approach here is restricted to examining the market value of water used for irrigation rather than the total socio-economic value of water in general, which would go beyond the scope of this analysis.

The hydrologic-economic model

As a starting point to illustrate and apply the conceptual framework presented in the second section, we propose a simple model in which we shall address the first of the management problems in economic terms, referring to the value of the blue water lost because of the change in land cover. As explained above, we do not refer here to the total socio-economic value of water as a resource, but to the market opportunity cost of irrigation water. We shall look at the eight agricultural districts of northern Aragon in northeast Spain, bringing to bear the relevant agricultural and hydrological data on this target area to estimate and assess the economic impact of the green water phenomenon. This exercise requires a hydro-economic model. The following sub-sections describe the basis for this model.

The blue and green water consumption and productivity model

Water requirements (CWR) and evapotranspiration [ETc = Kc * ETo, mm / month, where ETo is the benchmark evapotranspiration and Kc is the crop coefficient] for each crop and district are derived from Martínez *et al*. (1998) and García-Vera and Martinez Cob (2006). Crop water consumption (CWC) is calculated by accumulation of monthly evapotranspiration (ETm) over the full growing period (of m = n months):

$$CWC = 10 * \sum_{m=1}^{n} ET_m$$

Following the literature cited above, we define productivity in more than one way (with three measures). We obtain one first measure of the value of 'apparent productivity' per cubic meter of blue water for each crop in each district. The other two measures of productivity are based on the net margin on crops. The first of these two provides the total net margin per cubic meter of water, and the second expresses the differential net margin, DMN (irrigated minus unirrigated farming) per unit of water.

The hydrological model: run-off coefficients

The run-off (RO) coefficients in each of the two periods are obtained as follows:

$$RO_t = \frac{\sum_{i=1}^{n} P_t^i}{\sum_{i=1}^{n} Q_t^i}$$

where P^i_t and Q^i_t are precipitation and discharges at point i in year t, and n is the number of discharge points.

The variation in RO in the two long periods of $t_f - t_i$ years, δRO, where t_f is the final and t_i the initial year one, is obtained as:

$$\delta RO = 1 - \frac{\dfrac{\sum_{t_{i2}}^{t_{f2}} RO_t}{t_{f2} - t_{i2}}}{\dfrac{\sum_{t_{i1}}^{tf1} RO_t}{t_{f1} - t_{i1}}}$$

Hence, δRO is the average loss in the run-off ratio in the second compared to the first period.

Data set: the case study

History: A century at the mouth of the Ebro

Let us now describe the underlying facts in our case study in more detail. The annual outflow from the the River Ebro at its mouth in the early decades of the 20th century was only 15,000 hm^3 yr^{-1}. At that time, the Ebro's flow was scarcely regulated, and there were no large irrigation schemes. All of this changed with the construction of major dams and irrigation systems between 1950 and the early 1970s however, and the outflow at the mouth of the Ebro had fallen to roughly 15,000 hm^3 yr^{-1} by the end of this period.

At the same time, the Pyrenees and Pyrenean foothills were affected by mass migration which halved the population during the three decades after 1950 (Pinilla *et al*., 2008). This allowed forests, meadows and vegetation in general to grow free from human pressure. However, the river's flow has not stabilized since the period of these great transformations, and the annual volume of water flowing from the Ebro into the sea was below 10,000 hm^3 in 2005. In short, the flow from the Ebro into the Mediterranean has halved in just one hundred years.

In the fields of hydrology and environmental management, Gallart and Llorens (2003, 2004), Vicente-Serrano *et al*. (2004), López Moreno *et al*. (2006) and Delgado *et al*. (2010) have all built upon the work of García-Ruiz *et al*. (1996) to show that the shrinkage of the Ebro's flow cannot be fully explained through the usual hydrological models based on a constant run-off to precipitation ratio.

Bielsa *et al*. (2001) sought to explain the decline in the river's flow in terms of agricultural water use, which accounts for more than 90% of the physical consumption of water in the Ebro Valley, and in terms of other human uses. The data are stark. The combined increase in urban and industrial consumption in the Zaragoza metropolitan area (the largest city in the Ebro Valley) explains no more than 0.3% of the reduction, and no less than one and a half million additional hectares of very low efficiency irrigation would be required to explain it in terms of agricultural uses alone. However, only some 400,000 new irrigated hectares were added in the second half of the 20th century, which plainly falls far short. The result is clear: even on the assumption of maximum consumption, all human activity combined would not explain much more than half of the palpable decline in flow. This leaves the rainfall variable to provide at least a partial explanation of the volume of blue water lost, yet Cuadrat *et al*. (2007) show that there have been no statistically significant changes in average annual precipitation.

More recently, a number of papers have been published in the field of Hydrogeology containing up-to-date data. Rather than estimating water drawn off by human activity, López Moreno *et al*. (2008, 2010) examined water 'yields' in the Pyrenean catchment areas, which explain where almost half of the water currently flowing down to the last stretches of the Ebro comes from. As these are headwaters, impacts from human activity are negligible. The conclusions reached by these researchers are clear: after discounting the general effects of the known rise in temperature on flows (due to increased evaporation), the statistical 'residuals' remaining in the time series for effective run-off (*i.e.* the run-off reduction not explained by rainfall decreases) are very significant and are becoming even larger.

In short, a combination of the (statistically significant) rise in temperature and the considerable increase in the density of land cover is responsible for the volume of water that is no longer available in watercourses, either for human use or to maintain the ecological and geomorphologic balance of rivers. Direct evaporation and plant transpiration both fall within the category of 'green water flows' defined by Falkenmark (2003), meaning that part of precipitation that does not form part of surface water flows but is directly or indirectly returned to the atmosphere.

All in all, on examining the water contribution data at the mouth of the River Ebro for the last hundred years we cannot but agree with López Moreno *et al*. (2008), who conclude: 'The growth of vegetation following the abandonment of farmland in the study area is the only factor capable of explaining the detected change in the hydrological response of the Pyrenees'.

Specific data set for the case study

The hydrological information used to reflect the decrease of blue water in the region was obtained from Lopez Moreno *et al*. (2010). For the hydrological part of the model, we selected only six discharge points from the much longer list of gauging points close to the Pyrenees. Each of these points is located at the head of a major river in order to capture the evolution of discharge and the run-off coefficients for gross water volumes without taking into account human diversions and consumption. Figure 2 shows the gauging points

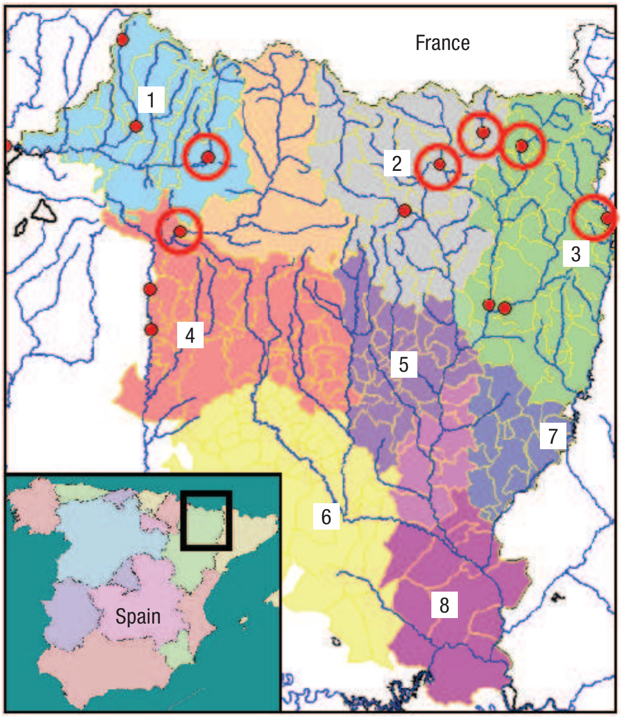

Figure 2. Agricultural districts (1, Jacetania; 2, Sobrarbe; 3, Ribagorza; 4, Hoya Huesca; 5, Somontano; 6, Monegros; 7, La Litera; 8, Bajo Cinca) and discharge gauging points (circled) in the province of Huesca, Northern Spain. Source: Own work based on López Moreno *et al*. (2010).

at which data on the recent evolution of inflows were obtained. Two periods are considered to capture the previous and “current” water equilibriums (1945-1975 and 1975-2004).

Turning to the agricultural data used, Table 1 shows a geographical breakdown of yields for each crop type in each district. This is the economic matrix of the problem, which we shall cross with the hydrological matrix obtained from the work of López Moreno *et al*. (2010).

As explained in the methodology, we present three measures of apparent productivity of water. A first one is based on the prices received by farmers (considering the yield, with water consumed per kilogram produced). The second, using the net value of irrigated land, and the third one, based on the difference in net value between irrigated and unirrigated land, both considering the blue water consumed per hectare (the last two rows of Table 1). In the former case, we use the value of output from irrigated farming for the period 1995-2006 considering the areas sown and crop yields for each district based on official Ministry of Agriculture data.

Results

Let us begin with the hydrological results. As explained for the general case, the run-off coefficients in each of the years *t*, RO_t, are obtained as:

$$RO_t = \frac{\sum_{dp=1}^{6} P_t}{\sum_{dp=1}^{6} Q_t},$$

where $\sum_{dp=1}^{6} P_t$ are the sum of precipitation at the 6 points in the year *t*, and $\sum_{dp=1}^{6} Q_t$ is the sum of the discharge at the 6 points in year *t*.

Table 1. Water productivity (€ m^{-3}) in the province of Huesca per district and crop

Crop	Districts[1]								
	Jac	**Sob**	**Rib**	**HH**	**Som**	**Mon**	**LL**	**BC**	**Total[2]**
Wheat	0.09	0.07	0.04	0.30	0.27	0.24	0.25	0.22	0.26
Barley	0.12	0.07	0.05	0.35	0.37	0.27	0.28	0.25	0.31
Other cereals (oats, etc.)	0.01	0.01	0.01	0.14	0.14	0.12	0.13	0.11	0.13
Corn	0.03	0.03	0.03	0.30	0.29	0.27	0.28	0.26	0.27
Rice				0.21	0.20	0.19	0.19	0.19	0.20
Proteaginose	0.00			0.00		0.48	0.66	0.48	0.48
Legumes (grain)	0.00	0.03	0.03	0.00	0.66	0.66	0.66	0.66	0.64
Sunflower	0.02	0.02	0.02	0.10	0.10	0.09	0.09	0.09	0.09
Other herbaceous oily plants	0.02	0.02	0.02	0.12		0.11	0.11	0.11	0.11
Tuber				1.08		0.77			1.04
Alfalfa	0.25	0.23	0.18	1.38	1.35	1.13	1.17	1.04	1.20
Other forage (tufted vetch, etc.)	0.95	0.95	0.60	2.67	2.67	1.12	1.12	1.12	1.69
Vegetables				7.65	3.55	14.32	3.10	2.65	3.17
Apple trees	0.05		0.05	0.61	0.61	0.53	0.61	0.48	0.53
Pear trees	0.18	0.18		1.78	1.78	1.53	1.78	1.35	1.50
Peaches and nectarines		0.16	0.00	1.60	1.60	1.38	1.60	1.21	1.28
Cherries	2.48		1.15	15.75	11.63	11.53	11.57	9.59	10.11
Plums	0.00			0.00			2.82	2.13	2.48
Other fruits, sweet fruits					2.86	2.92	2.94	2.91	2.91
Almond trees	0.00		0.00	0.01	0.01	0.01	0.01	0.01	0.01
Vines		0.13		1.33	1.33	1.34	1.33	1.33	1.33
Olives		0.08	0.08	0.78	0.78	0.78	0.78	0.78	0.78
Other woody plants						0.66	0.75	0.56	0.58
Apparent productivity	0.61	0.73	0.49	1.24	1.13	1.30	1.09	1.02	1.10
Total net margin (TNM) m^{-3}	1.6	1.4	0.6	0.3	0.4	0.6	0.6	0.5	0.75
Differential net margin (DNM) m^{-3}	0.8	0.7	0.3	0.2	0.2	0.5	0.6	0.5	0.475

[1] Districts: Jac, Jacetania; Sob, Sobrarbe; Rib, Ribagorza; HH, Hoya Huesca; Som, Somontano; Mon, Monegros; LL, La Litera; BC, Bajo Cinca. [2] Total average in the province of Huesca. Source: Own work.

Hence, the variation in RO in the two long periods of 30 years, δRO, is obtained as:

$$\delta RO = 1 - \frac{\dfrac{\sum_{t=1975}^{2004} RO_t}{2004-1975}}{\dfrac{\sum_{t=1945}^{1975} RO_t}{1975-1945}}$$

where $\dfrac{\sum_{t=1975}^{2004} RO_t}{2004-1975}$ is the average RO in the 2nd period, and the denominator is the average RO in the 1st period.

Table 2 shows the hydrological results that we shall use as the basis for the subsequent economic valuation.

The average percentage fall in the run-off coefficients (RO) δRO for the six gauging points selected is 5.4%. This result is robust to the choice of estimating either the average RO coefficients or the RO coefficient of the average P and D at the six points. Interestingly it is even robust to the choice of a more recent second period, as the reduction is 5.6% comparing 1995-2004 to the prior period (1945-1994), and it is 5.4% comparing the period 2000-2004 to 1945-1999. In any event, this percentage is a very conservative estimate of actual blue water reductions. A more accurate figure would, however, require a detailed hydrological study that would include other secondary headwaters further south.

We obtain the extra average volume per year V_t^{extra} simply as the precipitation in the 2nd period multiplied by the coefficient of the first, minus the current discharges (of the 2nd period, 1975-2004). Thus, the reduction in volume is estimated as the extra volume there would be if the former (1st period) run-off coefficients applied.

$$V^{extra} = P^{2nd} \cdot RO^{1st} - V^{current},$$

where P^{2nd} represents average precipitation in the 2nd period, RO^{1st} the average RO coefficients of the 1st period, and $V^{current} = V^{2nd}$ the current discharge volumes identified at the discharge points.

$$V^{extra,1975-2004} = P^{1975-2004} \cdot RO^{1945-1974} - V^{1975-2004}$$

Having estimated the blue water decline that can be geographically distributed based on the spatial structure of irrigation in the area considered, we assume that the loss for agriculture is evenly spread in spatial terms and affects all districts equally. Table 3 shows the result of the estimated reduction in flows caused by the increase in wild land cover in the 'water producing' areas.

It is likewise possible to calculate the area in hectares that could be irrigated with 65% efficiency (estimated average for the province) using the volume of lost blue water estimated above, assuming current requirements and crop distribution in each district.

Finally, we may value these areas of 'virtual' irrigation based on the localized productivity data given in Table 1. Table 4 shows the result of this procedure.

To sum up, an extra volume of 54.4 hm^3 would have been obtained if the RO coefficients of the first period, 1945-2004, had applied, and this water could have been used in line with current irrigation distribution patterns in an area of 5,900 ha in the province of Huesca. Based on our estimates of total net margin (TNM) productivity, this would yield € 27 million measured by the net margin of irrigated land. More interestingly, however, we estimate that the extra volume would generate an additional € 23 million (differential net margin), all others things being equal, given the difference between the net margin values of irrigated and rainfed farming systems, as the measure focuses on the differences in revenue obtained depending on the use or otherwise of these lost blue water resources.

Table 2. Precipitation (P), discharge (D) and run off (RO)

Period	Precipitation (hm^3)	Discharge (hm^3)	Run Off coefficient
1945-1974	8593	1021	0.12
1975-2004	8441	948	0.11

Source: Own work, data from López Moreno *et al*. (2010).

Discussion

The main aim of this paper has been to integrate theoretical and empirical knowledge from the field of hydrology [or eco-hydrology to use the term employed by Falkenmark and Rockström (2004, 2006)] with the fields of agricultural and environmental economics. This integration takes place via two issues that we understand to be important for Mediterra-

Table 3. Geographical distribution of run off looses (hm^3 per crop and per district)

Crop	Districts[1]								
	Jac	**Sob**	**Rib**	**HH**	**Som**	**Mon**	**LL**	**BC**	**Total[2]**
Wheat	0.09	0.03	0.02	1.14	0.21	0.37	1.01	0.68	3.57
Barley	0.11	0.01	0.08	2.73	0.96	1.05	2.49	1.13	8.56
Other cereals (oats, etc.)	0.00	0.01	0.00	0.06	0.02	0.09	0.16	0.03	0.37
Corn	0.00	0.00	0.00	3.11	1.04	4.96	2.41	2.25	13.77
Rice	0.00	0.00	0.00	0.81	0.02	0.58	0.53	0.39	2.33
Proteaginose	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.04	0.17
Legumes (grain)	0.00	0.00	0.00	0.01	0.01	0.02	0.01	0.06	0.11
Sunflowers	0.01	0.01	0.01	0.62	0.24	0.40	0.75	0.38	2.42
Other herbaceous oily plants	0.00	0.00	0.00	0.02	0.00	0.06	0.02	0.02	0.12
Tuber	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.02
Alfalfa	0.04	0.02	0.01	3.54	0.55	3.53	4.51	1.49	13.68
Other forage (tufted vetch, etc.)	0.16	0.17	0.14	0.37	0.08	0.33	0.52	0.22	2.00
Vegetables	0.01	0.00	0.01	0.06	0.01	0.52	0.02	0.03	0.65
Apple trees	0.00	0.00	0.00	0.04	0.01	0.02	0.39	0.45	0.91
Pear trees	0.00	0.00	0.00	0.02	0.04	0.01	0.44	0.72	1.23
Peaches and nectarines	0.00	0.00	0.00	0.02	0.01	0.03	0.49	2.09	2.65
Cherries	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.10	0.12
Plums	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.03	0.07
Other fruits, sweet fruits	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
Almond trees	0.00	0.00	0.00	0.05	0.02	0.03	0.06	0.04	0.20
Vines	0.00	0.00	0.00	0.01	0.45	0.00	0.02	0.09	0.58
Olives	0.00	0.00	0.00	0.16	0.06	0.09	0.18	0.26	0.77
Other woody plants	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02
Total volume	0.43	0.27	0.29	12.81	3.73	12.24	14.06	10.53	54.36

[1] Districts: Jac, Jacetania; Sob, Sobrarbe; Rib, Ribagorza; HH, Hoya Huesca; Som, Somontano; Mon, Monegros; LL, La Litera; BC, Bajo Cinca. [2]: Average in the province of Huesca. Source: Own work based on data from López Moreno *et al*. (2010).

nean climate regions, like that of the case study, where water is scarce. On the one hand, we propose a conceptual framework in order to incorporate an economic standpoint to the observed reduction of water resources due to free growth of vegetation in some depopulated areas in northeastern Spain (López Moreno *et al*., 2006, 2008, 2010). The second issue at stake, closely related, is to close the gap between recently acquired knowledge in the natural sciences and the day-to-day procedures applied by water, land and territorial managers in this region. We believe that there are a number of valuable insights to be gained for improved water management, as the papers of Zhang *et al*. (2001), Andreassian (2004), Hoff (2006), Sun *et al*. (2006) or Tague and Dugger (2010) have pointed out.

Table 4. Total net margin (TNM) and differential net margin (DNM) lost (millions of Euros)

District	TNM	DNM
Jacetania	0.691	0.333
Sobrarbe	0.375	0.181
Ribagorza	0.178	0
Hoya de Huesca	4.221	2.032
Somontano	1.312	0.632
Monegros	6.807	6.455
La Litera	8.451	8.014
Bajo Cinca	5.361	5.084
Total	27.396	22.729

Source: Own work.

The general framework consists basically of joint management of water, biomass and carbon sequestration, subject to certain important constraints in terms of biodiversity, soil conservation and fire risks. This is a broader but similar approach than that of Baskent and Küçüker (2010). These three "control variables" are the operational levers of a much broader and more challenging problem, namely, how to provide the water and energy needed while containing atmospheric carbon emissions, subject to other constraints like control of desertification and biodiversity loss.

This leads us to a more specific conclusion: the current separate management of blue and green water is a partial approach that fails to take account of the hydrological options available in the region. In this light, combined management of green and blue water is needed in order to know real water availability and the real risks faced by the environment, the economy and the population of a territory.

Starting from this general position, we have taken a small step towards highlighting some economic aspects of the variables and physical relationships involved. We have estimated a part of the economic losses to farming associated with this extraordinary increase in the density of land cover referred above. This is only a small part of the costs and benefits brought by such a big change in the forest-water-land environment. Our assessment of these losses is based on the difference in the net agricultural margin obtained from irrigated and unirrigated farming. This exercise revealed significant economic losses, even starting from highly conservative assumptions in our estimates of the decline in available water resources.

As long as these calculated effects are probably slightly more than the "tip of the iceberg", the potential ramifications of this study are evident. It remains to complete the economic valuation of the parts of the puzzle we have described but have not analyzed, the most obvious of which would include lost hydroelectric power and the possibility of using 'surplus' biomass to create value, whether in the form of power or via the opportunity to increase animal husbandry and timber output.

We hope that further transdisciplinary studies of this kind will highlight the need to advance our specific knowledge in these fields. As we are all too well aware, the very real problems go far beyond the narrow bounds of individual scientific disciplines, and it is therefore highly likely that the social sciences will increasingly demand data and insights from the natural sciences in the future.

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