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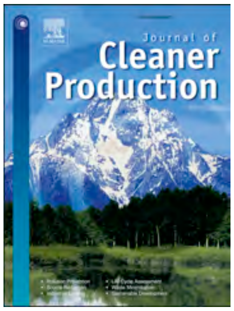

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Environmental flow management: an analysis applied to the Ebro River Basin

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Abstract:

Environmental flows (EF) define the quantity, timing and quality of river flows needed to preserve freshwater ecosystems while assuring the continuity of human use. Insofar as they reduce water availability and condition agricultural and industrial uses, EF represent a constraint, but they also hold out new opportunities for development. This study focuses on the final stretch of the Ebro River (Spain) and on the competing environmental uses of water (the Ebro Delta is a biosphere reserve) and economic uses (irrigation and electricity generating). Environmental flows in the Ebro Delta are currently managed only from the Mequinenza dam and reservoir in eastern Aragon, and the resulting outflows have more than once driven the level of the reservoir down to critical environmental levels in recent years. In general, this management policy has also caused a range of negative environmental and economic impacts in the area. However, other alternatives exist, which could foster both more cooperative and equitable flow allocations, and the development and sustainability of the Ebro Basin. To this end, we develop a water management model to simulate scarcity scenarios and measure the associated environmental flow default rates assuming current productive uses. Our findings confirm that it is not possible to guarantee EFs in the delta without reservoir-based water management so as to ensure the compatibility of EFs with the irrigation and hydroelectric activities. Moreover, the existence of more equitable and cooperative water management options would reduce water pressures on Mequinenza dam and so help fulfill the subsidized irrigation commitments established in Aragonese Lower Ebro Plan.

Keywords: Environmental Flows, Water Resource Management, Ebro River Basin, Game Theory

1. Introduction

The importance of water for life, for the environment, for human beings and for industries of all kinds is indisputable. However, the quality and availability of the resource are affected by numerous variables, including increases in upstream use and climate change (Alcamo et al., 2007; IPCC, 2014), spontaneous revegetation and so forth, all of which combine to diminish fresh water availability (Gerten et al., 2008). The European Water Framework Directive (WFD) was enacted partly in response to declining water availability (European Communities, 2000). In particular, the WFD requires member States to achieve good ecological status (GES) in all water bodies and river basins, and to establish Environmental Water Requirements (EWR) and regulate environmental flows (EF) in all of Europe's rivers, defining the quantity, timing and quality of the water flows necessary to ensure sustainability under variable conditions, see Acreman and Ferguson (2010). In this context, our study focuses on the final stretch of the Ebro River (Spain) analysing the competing EF and other economic uses in the Ebro Delta (a Biosphere Reserve).

In economic terms, EFs present a serious constraint, particularly for arid and semi-arid regions, because they reduce the volume of water available for consumption and condition agricultural and industrial uses (Bonsch et al., 2015). However, the GES of water bodies and river EF also provide environmental and economic benefits for users and non-users alike, see Ilija Ojeda et al. (2008), Loomis (2000), and Perni et al. (2012). In fact, environmental flows often generate new development

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opportunities in the areas affected, although can result in social conflict between potential users—see, for example, the work of Qureshi et al. (2010), who address the question of who should receive the profits and bear the costs implicit in any management of environmental flows.

Irrigation communities have long existed to regulate and share the precious resource that is water, some of them going back centuries, even millennia (Sagardoy, 2001). The Water Tribunal of Valencia, whose jurisdiction is a legacy from the time of Moorish rule in eastern Spain is an example. Despite the argument that human beings are often selfish and will sometimes exhaust and destroy shared resources (Gordon, 1954; Hardin, 1968), it seems when the resource is water that communal bodies in fact spring up to handle the tasks of conserving and allocating water, contrary to Hardin's "tragedy of the commons" theory.

Nevertheless, conflicts related with water do exist and when rivers or their basins do not lie entirely within the borders of a single nation, disputes can become bitter and ingrained (Wolf, 1998). Even under the same flag, water can become a source of conflict, as in the case of the Cauvery River in India; in California (Hanak et al., 2011); along the Colorado River (Fradkin, 1981); and in the last two decades in Spain, where the *Plan Nacional del Agua* directly affected Ebro water use and water transfers from the Tagus to the River Segura. The outline of the National Water Plan has been at the root of ongoing political wrangling ever since.

This study seeks the best solution to the water conflicts associated with the final stretch of the Ebro River (Spain), where water uses are already bumping up against their limits, as we shall see below. The Ebro River runs for 910 km in a south-easterly direction across northeast Spain to its delta on the Mediterranean coast midway between Barcelona and Valencia. It has the largest discharge of any Spanish river, and its drainage basin, at 85,500 square km, is also Spain's biggest. The Ebro River Basin provides water to more than three million people living in over 1,700 towns and villages, but it suffers from high levels of evapotranspiration, and low, irregular rainfall (Novau and Campo, 1995). Moreover, a slight decline in mean annual rainfall has been observed over the last eight decades (Valencia et al., 2015). According to Milano et al. (2013) and Sánchez-Chóliz and Sarasa (2015), in fact, a general downward trend in water availability is observable in the Ebro River Basin as a whole, a phenomenon that is strongly supported by statistics from the Tortosa gauging station. This only increases the pressure on water alternative uses.

The legal EFs in the Ebro Basin, and in particular for the Ebro Delta, are fixed and regulated by the Ebro Basin Authority (*Confederación Hidrográfica del Ebro* or CHE in its Spanish acronym), which is also responsible for the preparation, review and implementation of annual management plans for the Ebro River Basin. The process involves drawing up preliminary plans, which are submitted to public scrutiny by all stakeholders (irrigators, industry, local councils and environmental organizations) as required by the WFD (Ballester and Mott Lacroix, 2016).

Water use on the final stretch of the Ebro River is a fiercely competitive matter. Not only do upstream uses compete with uses in the final stretch, but these downstream environmental and economic uses also vie with each other. Priorities include the water requirements to guarantee environmental conditions in the Ebro Delta (a Biosphere Reserve) and to control the salinization of its farmland. Reservoir GES is another prime environmental concern, especially at the Mequinenza dam. Key economic uses include irrigation and hydroelectric generating. Rice is the main irrigated crop in the Ebro Delta, and this traditional activity is essential to maintain the local flora and fauna. Water is also drawn off from Mequinenza reservoir for subsidized irrigation in neighboring wetlands (Aragonese Lower Ebro Plan). Finally, there are also several important hydroelectric power plants along the river's lower stretch of the river. For example, the Mequinenza power plant has approximate annual turbine capacity of some 4,800 hm^3 a year (equal to 75% of Mequinenza's annual inflows) generating capacity of 324,000 Kw and output equal to around 500 Gw-h).

Conflict with the autonomous region of Catalonia is a further issue affecting water management in relation to the Ebro Delta and most of the Segre River Basin, one of its main tributaries, both of which are within Catalonia's regional borders. The strong Catalan nationalist movement seeks secession from Spain and to turn Catalonia into an independent state. This has resulted in a largely contrarian policy on the part of the Catalan authorities reflected in uncompromising demands to guarantee environmental needs of the Delta while excluding Ebro reservoirs like Rialb, which is located in Catalonia and which the nationalist-controlled regional government hopes to appropriate exclusively for local irrigation and future transfers to the city of Barcelona.

A full study of this complex conflict is beyond the scope of this article, see Saez et al. (2015), but the key to any possible solution will involve the regulation criteria applied to the lower Ebro reservoirs. For this reason, we develop a water management model which allows us to simulate scarcity scenarios and measure environmental flow default rates. For the sake of simplicity, the model assumes that the volume of irrigation in the delta will remain constant, which allows us to exclude these uses from the analysis. We likewise assume that there will be no additional water demand for hydroelectric generating, since no-one today is lobbying for an increase of this activity. As a result of these constraints, our model focuses mainly on the hydrological aspects of the problem (dam reoperation) and Ebro Delta EF fulfilment. We also tackle the current management of environmental flows on the final stretch of the Ebro and assess possible alternatives to answer the question: Is there a management criterion that would assure Delta EFs and at the same time reduce water pressures on Mequinenza while maintaining current irrigation and hydroelectric uses are and allowing the completion of subsidized irrigation plans?

Environmental flows in the Ebro Delta, which are gauged at Tortosa, are currently regulated by the Mequinenza dam alone, although other options could be considered. In our case study, we look at three reservoirs situated in the final stretch of the Ebro River Basin, namely Mequinenza, Rialb and Ribarroja, which have respective capacities of 1,530, 403 and 210 hm^3. Other theoretical alternatives also exist, such as the El Grado and Barasona reservoirs for example, but they are not viable due to overuse of their water for irrigation and electric power generation and to their size.

We then go on to use game theory, especially bargaining games, alongside the management model developed in order to account for different institutional frameworks and assess the proposed alternatives. To this end, we develop utility functions based on the reservoirs' average levels and fluctuations obtained from the model so as to shed light on the opportunity costs associated with different management alternatives. Our research aims to contribute to the settlement of water conflicts and to foster more cooperative and equitable flow allocations in the final stretch of Spain's Ebro River Basin in order to assure the future development and sustainability of the area. This is achieved by linking a combination of methods based on a proposed water management model with game theory in order to account for the influence of different institutional frameworks.

The rest of the paper is organized as follows. Section 2 reviews the existing literature on water allocation. In Section 3, we analyse time series from the gauging stations covering a period of 50 years to establish a correlation between water inflow and outflow along the final stretch of the River Ebro as a basis for the development of our water management model. Section 4 describes the initial results from our simulations, while the results obtained from the different game theory scenarios are outlined in Section 5. We end with a discussion of our main conclusions and policy recommendations in Section 6.

2. Review of the literature

Scholarly interest in water conflict resolution and in assessing water both as an economic input and natural resource, has increased in recent years (Hipel et al., 2015). As a consequence, numerous methodologies and models have been proposed to establish best water allocations based on the constant rise in calculation and data management capabilities, and on progressive developments in game theory.

To begin with, numerous hydro-economic models have been proposed to evaluate water allocation strategies, see for example George et al. (2011), and to analyse water-related issues such as inter-sector water allocation, water markets and pricing, conflict resolution, land-use management, climate change and drought among others. Various proposals of this kind have recently appeared, including Pulido-Velazquez et al. (2008), who develop a hydro-economic model to establish the shadow value of water and assess the opportunity cost of environmental requirements; Akter et al. (2014), who describe a hydro-ecological-economic model designed to assess water reallocation benefits in the Murray-Darling Basin (Australia); and Kahil et al. (2015) and Kahil et al (2016), who asses different possible water policies in scarcity and drought scenarios to handle climate change adaptation in arid/semi-arid regions. More details and a detailed review of the literature on hydro-economic models will be found in Harou et al. (2009). Alongside these models, we also find papers on the subject of dam reoperation, such as Bednarek and Hart (2005), who discuss how dam management could drive better biological status in tailwaters, and Watts et al. (2011), who show the importance of dam reoperation in the service of climate-change adaptation. These models and methodologies capture relevant technical, physical and economic information on irrigation and production technologies, water flows, the technical efficiencies of different uses, benefits, demand patterns and so forth.

Meanwhile, computable general equilibrium (CGE) models provide another tool which has been widely used to examine water management issues in recent years. Among others, a CGE model of the US economy developed by the USDA Economic Research Service (ERS) is presented in Robinson et al. (1990), while Seung et al. (1999) used a CGE model to evaluate surface water reallocation policies (water rights sales) at the Stillwater National Wildlife Refuge in Churchill County, Nevada, and Calzadilla et al. (2010, 2011) develop a global CGE to analyse the sustainability of irrigation. Another frequently cited example of a multi-regional CGE model is The Enormous Regional Model or TERM designed by Wittwer (2012) and applied by Wittwer and Dixon (2013) to analyse water buyback policies in the Southern Murray Darling Basin under drought conditions. Other water-related CGE models have also been developed to address technological changes applied to irrigation water management, see Philip et al. (2014).

Hydro-economic and CGE models have been widely used to assess water allocations, and in this paper we have chosen to combine a water management model with game theory, and in particular with bargaining games, in order to address the impact of different institutional frameworks and to assess the contribution of the proposed alternatives to the attainment of environmentally sustainable solutions.

This combination of methods for the analysis of the Ebro Delta in Spain is in line with prior uses of game theory in conflicts of this type, such as the Graph Model for Conflict Resolution (GMCR), which uses game theory to find the best allocation within a user-friendly windows operating environment. GMCR is described in Hipel et al. (1997) and has been successfully applied to an environmental conflict in North America. Other similar models are the Interactive Computer-Assisted Negotiation Support system (ICANS) developed by Thiessen and Loucks (1992), which offers bargaining solutions for dynamic, multi-issue, multi-party negotiation problems, and the Water Allocation System (WAS) used to analyse the water situation in the Middle East (Fisher et al., 2002). We may note here that game theory provides an explanation for the kinds of communal, cooperative behaviour in question here (Jager et al., 2016), and it appears likely that the presence of stakeholder associations is a key guarantee of water availability and quality (Aumann, 1964; Ostrom, 1990). Cooperative games have recently been used in connection with water issues in Abed-Elmdoust and Kerachian (2012) to look for the best water allocation in a context of fuzzy payoffs, and in Kahil et al. (2016b), who use a cooperative game theory framework to show the economic and environmental benefits of cooperation for stakeholders in the Jucar River Basin (Spain). Other games have also been used for similar purposes in Kerachian et al. (2010), where a model is developed based on Rubinstein's bargaining model (Rubinstein, 1982), to resolve conflicts of stakeholder interests in the joint use of surface and groundwater resources.

3. Data and Methodology

3.1 Data

As mentioned in the introduction, the legal environmental flows for the Ebro Delta at Tortosa gauging station, described in Table 1, are fixed and regulated by the Ebro Basin Authority. At a yearly volume equal to approximately 25% of the mean yearly runoff of 12,500 hm^3 from the Ebro River at Tortosa between 1984 and 2014, well above the level of 10% - 20% normally set for EWR, these EF volumes are very large and represent a significant constraint.

Table 1. Proposed environmental flows at Tortosa gauging station

	Oct	Nov	Dec	Jan	Feb	March	April	May	June	July	August	Sep	Total
Minimum flow (m^3/s)	80	80	91	95	150	150	91	91	81	80	80	80	95.58*
Monthly contribution (hm^3)	214.27	207.36	243.73	254.45	369.36	401.76	235.87	243.73	209.95	214.,27	214.27	207.36	3,016.4

*Annual average, source: CHE (2014)

Our database includes daily data on water volumes measured at the gauging stations and water discharges from each reservoir situated in the Ebro River Basin from October 1964 to September 2014, obtained from the Gauging Yearbook (MAPAMA, 2016). However, the environmental flows we are concerned with are set monthly, and we have converted daily figures accordingly.

Meanwhile, the Ebro Delta environmental flows measured at Tortosa are managed solely on the final stretch of the Ebro River. Water inflow along the final stretch comes mainly from upstream and from the Ebro's two main tributaries, the Segre and the Cinca. Our analysis includes the Mequinenza, Rialb[1] and Ribarroja reservoirs, which have respective capacities of 1,530 Hm^3, 403 Hm^3 and 210 Hm^3. The Mequinenza dam collects water from upstream on the Ebro River, while Rialb reservoir receives water flows from the Upper Segre River. Meanwhile, both the River Cinca and the Segre flow into Ribarroja reservoir, where the outflow from Mequinenza also ends up, making Ribarroja a junction of the three rivers. Figure 1 provides a schematic representation of the final stretch of the River Ebro; a map is provided in the Supplementary Information (SI) (Figure SI1).

The monthly water inflows at these three reservoirs, the flows gauged at Tortosa and the flows measured at Serós gauging station reduced by Rialb inflows represent the key variables in the water management model presented in the following subsection. Water inflows in the last stretch of the Ebro are shown in Table SI1 in SI.

[1] Rialb is a new reservoir and the water inflow data comprise actual monthly figures from 1964-1981 (Ponts gauging station) and from 2000-2014 (Rialb reservoir). Meanwhile, annual data for Rialb between 1981 and 2000 were estimated by linear correlation with figures from Serós gauging station. Monthly data were assigned proportionally based on actual data for 2000-2014.

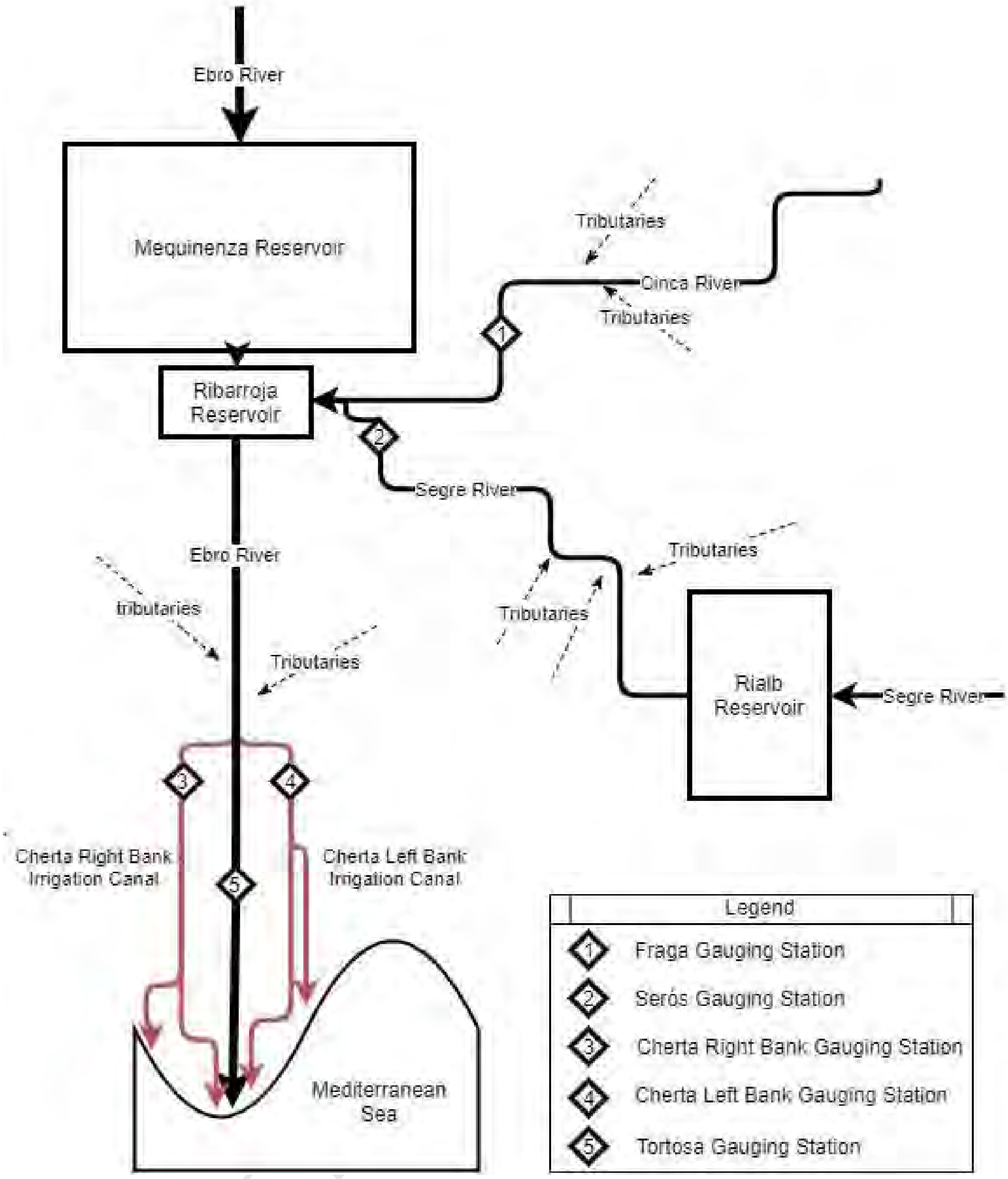

Figure 1. Schematic representation of the final stretch of the Ebro River. Source: Own work.

3.2 Methodology

Using monthly data obtained by the gauging stations over the last 50 years (1964-2014), we shall establish a monthly correlation between *water inflow* in the final stretch of the River Ebro and *water outflow* (measured at Tortosa). The data used comprise inflows observed at Mequinenza and the flows measured at the Tortosa, Fraga and Serós gauging stations, see Table SI2 in the SI. However, this estimation suffers from two serious problems. One consists of the impact on the monthly flows measured at Tortosa over the last two decades from artificial floods released for regulation purposes from Mequinenza dam since 2002 in order to guarantee EF at Tortosa, as well as the continuous water demand for use in hydropower operations since 1964. The other is the lack, or relative unreliability, of data from the 1990s. For this reason, we finally opted to use only data covering the period 1964-1988 for our initial and auxiliary estimation. Moreover, this estimation was made on an annual basis to smooth the impact of artificial floods, monthly regulation and water demand for electricity generating.

We performed a regression applying the ordinary least squares (OLS) method to the annualized data, with the following result.

$$\widehat{W}_t = 1.04\, W_t - 1{,}545.54\ ;\ R^2 = 0.944 \quad (1)$$

Where $\widehat{W}_t$ represents the estimated annual water outflow (measured at Tortosa) and W_t represents annual water inflow along the final stretch of the Ebro measured as the sum of inflow from Mequinenza reservoir and the inflows from the Fraga and Serós gauging stations. The estimated coefficient (1.04) means that water inflows should be increased by almost 4% to account for contributions from rainfall and minor tributaries. Meanwhile, the model constant suggests that withdrawals by irrigation canals plus other losses are around 1,545 hm^3 each year.

Starting from (1), we can obtain the monthly flows at Tortosa used in the analysis and in our simulations as follows,

$$\widehat{W}_t^m = 1.04\, W_t^m + \alpha_m\ ; \quad m = 1,\ldots, 12. \quad (2)$$

Where $\widehat{W}_t^m$ represents the estimated monthly water outflow in Tortosa, W_t^m represents the monthly inflows from Mequinenza, Fraga and Serós, the coefficient is the same as in (1); and the monthly constant, α_m, is obtained by dividing up the constant (-1,545.54 Hm^3) proportionally to the monthly flow data of the two main irrigation canals on the final stretch of the Ebro. These canals, both of which are located at Cherta (10 km upstream from Tortosa), have drawn off between 1,085 and 1,343 Hm^3 annually over the last 20 years

Meanwhile, the coefficient of 1.04 obtained in (1) may initially seem an excessively tough hypothesis in this monthly extension, but we believe it to be acceptable, given the difficulty of obtaining better monthly coefficients from the data currently available. Keeping the coefficient means assuming that the monthly contributions from rainfall and tributaries in the final stretch of the Ebro are proportional to the monthly contributions in the rest of the river basin. This hypothesis also incorporates the expected monthly variation as shown in the monthly histogram from Figure 2, where we can see the monthly inflows in 1964-2014 as a percentage of total inflows obtained from the Gauging Yearbook for Mequinenza reservoir and Fraga and Serós gauging stations.

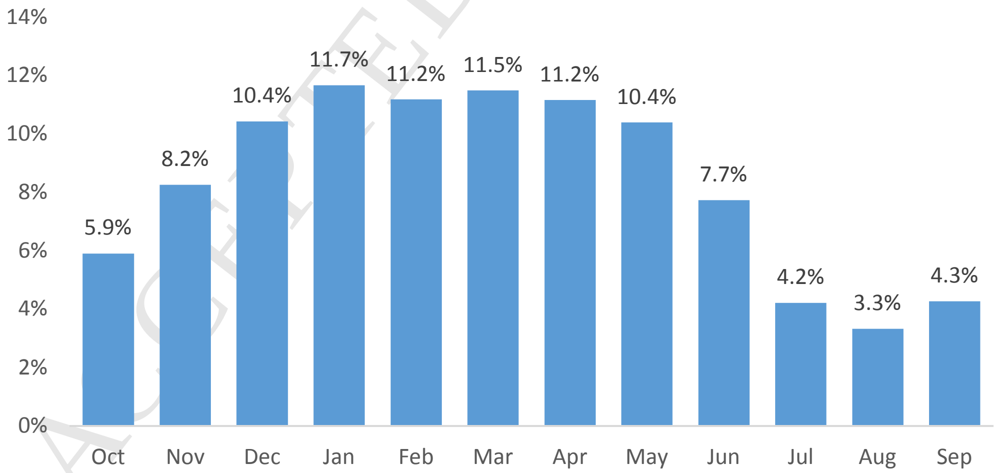

Figure 2. Monthly inflows in 1964-2014 as % of total inflows in the period

Meanwhile, the criteria applied to monthly distribution of the constant -1,545.54 Hm^3 allows us to assume that these withdrawals are proportional to their major component (i.e. withdrawals by the Cherta irrigation canals), which account for an average of approximately 80% according to data from the Gauging Yearbook. Table 2 presents the monthly values of the monthly constant α_m. This sharing criterion is consistent with the constant Delta irrigation assumed for the sake of simplicity.

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Table 2. Determination of α_m

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Total
-158.98	-117.21	-102.14	-63.71	-44.94	-74.09	-146.47	-170.08	-166.88	-171.73	-168.85	-160.45	-1,545.54

Finally, let us consider the meaning of equations (1) and (2), and therefore of the water management model generated. Equation (1) describes a "theoretical flow" at Tortosa defined for a scenario where there is no regulation or intervention via artificial floods. It is not therefore a description of the natural stream, but an approximation to an annual flow without institutional intervention based on the data actually available. Equation (2) is an alternative to the available monthly data[2]. As we shall see, however, the referential scenario defined by (1) and (2) is useful, allowing us to answer the two main questions posed: Are current and regulated environmental flows acceptable? And, are fairer and more cooperative management alternatives possible?

Having obtained (1) and (2), we can now simulate and analyse alternative scenarios based on the actual data for the purposes described in the introduction. Significantly, the model allows restrictions to be placed on the admissible levels in reservoirs, so that we can assess falling water availability in line with the downward trend in measurements taken at Tortosa (Sánchez-Chóliz and Sarasa, 2015), caused by increases in upstream use, the effects of climate change and revegetation (Bielsa et al., 2011), among other factors. Finally, we can also assess compliance with the mandatory environmental flows established by the Ebro River Authority.

4. Results of alternative management scenarios

In this section, we will present two blocks of simulations. Firstly, we analyse the effects of scarcity scenarios designed in line with current debates and proposals based on the impact of climate change and the higher environmental flows demanded by Catalonia. We then examine our own proposed water management strategies to assure compliance with regulated environmental flows while maintaining current water uses in the Ebro Delta.

In order to study current water availability and compliance with regulated EF in the final stretch of the Ebro River, we may use equation (2) to simulate a monthly flow regime without dams or reservoirs in our first block of scenarios. Focusing on the possible future effects of climate change and the higher EF demanded by Catalonia, the different scenarios (results shown in Table 3) may be summarized as follows:[3]

- Current Flows (CF) Scenario. Monthly flows are defined by equation 2 and actual inflows obtained from the Gauging Yearbook. The environmental flows are obtained from CHE (2014), as shown in Table 1 above. This scenario approximates the actual figures while smoothing changes caused by regulation and increases in irrigation demand over the last two decades.

[2] Hydroelectric uses are not included because they are assumed to remain constant. Experience over the last 20 years shows that hydroelectric uses have not posed a problem for Mequinenza in guaranteeing EF in the Ebro Delta. Moreover, no-one today is lobbying for a reduction of hydroelectric generating and recent plans do not provide for additional water demands in this area.

[3] The scenarios defined are intended rather to provide qualitative information (sensitivity analysis) than quantitative data, so the variations of 10% in Scenario HEF and of -20% in Scenario LFCC are merely arbitrary. However, 20% is in line with some forecasts of possible reductions in the stream flow of the Ebro River from 2040 onwards, (see, for example, Alvares et al., 2009).

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- Higher Environmental Flows (HEF) Scenario. This is similar to the CF scenario but it includes a 10% increase in environmental flow requirements. This scenario allows us to evaluate sensitivity to changes in EF.
- Scenario Lower Inflows due to Climate Change (LFCC) Scenario. Again, similar to the CF scenario but assuming a 20% fall in inflows due to the impact of climate change.
- HEF&LFCC Scenario. This combines scenarios "HEF" and "LFCC" and is consistent with the expected future situation due to tougher conditions.

Table 3. Natural stream simulation results

Scenario	Failed months		Failed years	
	Number	%	Number	%
CF	62	10.3%	0	0%
HEF	80	13.3%	0	0%
LFCC	132	22%	2	4%
HEF&LFCC	150	25%	2	4%

Source: Own work.

The "failed months" column refers to the number of months in which regulated environmental flows would not have been met by the flows obtained from the simulation, while "failed years" represents the number of years in which the total annual water volume measured at Tortosa would be lower than annual environmental flow requirements. The simulation covers 600 months from 1964 until 2014.

In the Current Flows (CF) Scenario, there are 62 months in which environmental flow requirements could not have been met without human intervention, as shown in Table 3.[4] Hence, compliance with the environmental flows established for the Ebro Delta in our model would be very difficult without infrastructure (reservoirs and dams), and water management is therefore crucial to meeting EF requirements. It also confirms the claim that Ebro water uses are already bumping up against its limits, as mentioned in the Introduction. Furthermore, the number of failed months increases in the other scenarios, which means that we should not expect any improvement in the coming decades, mainly because of climate change. This is a relevant finding, especially in view of proposals made by the Catalan Government (ACA, 2007; CSTE, 2015), which would impose much greater demands on the system, see Table SI3 in the SI.

We address our second block of simulations under this same framework, again using equations (1) and (2). Specifically, we analyse the impacts associated with two basic water management strategies. The first is *long-term regulation*, a soft alternative based on optimal monthly levels which are the same for every year and established by means of a conditional optimization procedure. This simulation is designed to achieve and maintain optimal monthly water levels for each reservoir every year. The second, *monthly regulation*, consists of making timely, targeted discharges to meet specific water and flow requirements so as to fulfil environmental flows. This second alternative may or may not be complementary with the first. The model optimization assumes as a constraint that the level of any reservoir must be above 50% of capacity in order to preserve ecosystems.

For the sake of simplicity, we shall take the Current Flows (CF) Scenario (which does not impose tougher requirements or reductions in water availability) as the base scenario for further simulations. In the case of both long-term regulation and monthly regulation, the optimization policy is implemented based on the data obtained from the Gauging Yearbook, and we simulate the potential impacts of the policy for each of the three reservoirs both separately and simultaneously.

[4] These flows represent approximately 25% of mean yearly runoff at Tortosa. Compliance would undoubtedly be greater if requirements were set lower. However, these stringent conditions have been collectively agreed by Ebro water users through the pertinent institutional mechanisms.

The basic optimization constraints for these simulations consist of maximum and minimum reservoir levels. The maximum is determined by the spillway level, but the minimum level is merely posited at around 50% of each reservoir's capacity. This constraint is based on two criteria, no area should be strong disadvantaged in order to favour another, and discharges for all reservoirs should be limited so as to avoid harming the local flora and fauna and to favour tourism and residential development. When a reservoir does not participate in management measures in any simulation, its level is assumed to be fixed at 75% of total capacity in volume terms. When monthly regulation is handled jointly by more than one reservoir, meanwhile, we assume for the sake of simplicity that the water used is shared, 50% coming from Mequinenza, 33% from Rialb and 17% from Ribarroja. The proportions are 65% and 35%, respectively, when only Rialb and Ribarroja contribute.

The results associated with both long-term and monthly regulation strategies in different situations for the period 1964/1965-2013/2014 are reflected in Table 4, while the optimum monthly levels obtained from long-term regulation are provided in Table SI4 in the SI. Table 4 shows the results for the main variables modelled (i.e. reservoir level, water volume and number of EF failures) at Tortosa. In particular, the first and second columns indicate the reservoirs that shoulder the burden of long-term and monthly management of environmental flows, while the third reports the number of failures to comply with regulated EF. The fifth column shows the minimum water levels reached at each reservoir, and the sixth shows the simulated average level over the fifty years of the study period. The percentage of total capacity associated with the minimum and average levels is also given. This table also presents the values of the utility functions, which we will define later in Section 5.

Note that the Current Flows scenario in Table 3 is the same as the scenario in Table 4 involving no long-term or monthly regulation, so the number of failures is the same in both. Note also that some of the scenarios presented in Table SI4 of the SI match those long-term scenarios in Table 4 that do not involve any kind of monthly regulation, so that the number of failures coincides.

As may be observed from Table 4, when management policy is applied at only one reservoir, its water levels are lower than when management policy is implemented by all. Likewise, it is plain that long-term planning strategies implemented by one or more reservoirs reduce the number of failures compared to the CF scenario (see Table 3). However, long-term planning alone cannot assure EF compliance at all times, eventually making short-term planning inevitable.

Table 4 also reveals that all of the alternatives involving monthly regulation by one or more reservoirs display a zero failure rate, ensuring compliance with the environmental requirements of the Ebro Delta. This confirms the existence of different alternatives to fulfil EF at Tortosa assuming the current uses for irrigation and hydroelectric power plants. These alternatives could be achieved either by means of intervention at Mequinenza alone, CHE's current option, or by cooperation between reservoirs. In other words, cooperative options exist and they are efficient.

Finally, although monthly planning is sufficient to fulfil Tortosa EF requirements, the environmental impact on the regulating reservoir and the surrounding area can be very adverse, as water volumes occasionally fall below the minimum level of 50% established in our model. This happens especially if monthly planning is not carried out in partnership.

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Table 4. Water Management Results 1964-2014

Long-term	Monthly	Fails	Reservoir	Minimum Level	Average Level	Standard Error (SE)	Unforeseen Deviation (UD)	Minimum Volume%	Average Volume%	U_i(SE)	U_i^*(UD)
All reservoirs	None	16	Mequinenza	111.64	115.50	2.75	0.19	62%	77%	112.75	115.31
			Rialb	419.42	422.55	2.12	0.31	67%	76%	420.44	422.24
			Ribarroja	64.50	66.84	0.91	0.00	60%	75%	65.93	66.84
	All reservoirs	0	Mequinenza	111.64	115.48	2.76	0.31	62%	76%	112.72	115.17
			Rialb	416.14	422.48	2.18	0.86	58%	76%	420.30	421.62
			Ribarroja	63.10	66.81	0.94	0.28	51%	75%	65.87	66.53
	Only Mequinenza	0	Mequinenza	110.88	115.46	2.77	0.50	59%	76%	112.69	114.96
			Rialb	419.42	422.55	2.12	0.31	67%	76%	420.44	422.24
			Ribarroja	64.50	66.84	0.91	0.00	60%	75%	65.93	66.84
	Only Ribarroja and Rialb	0	Mequinenza	111.64	115.50	2.75	0.19	62%	77%	112.75	115.31
			Rialb	410.26	422.40	2.39	1.57	44%	76%	420.01	420.83
			Ribarroja	61.34	66.78	1.04	0.61	42%	75%	65.74	66.16
Only Mequinenza	None	20	Mequinenza	111.27	114.80	2.51	0.03	61%	74%	112.29	114.77
			Rialb	422.50	422.50	0.00	0.00	76%	76%	422.50	422.50
			Ribarroja	66.99	66.99	0.00	0.00	76%	76%	66.99	66.99
	All reservoirs	0	Mequinenza	110.47	114.78	2.50	0.21	58%	74%	112.28	114.57
			Rialb	417.49	422.42	0.52	0.73	61%	75%	421.90	421.69
			Ribarroja	64.92	66.96	0.22	0.30	62%	76%	66.74	66.66
	Only Mequinenza	0	Mequinenza	109.64	114.75	2.49	0.42	55%	73%	112.26	114.33
			Rialb	422.50	422.50	0.00	0.00	76%	76%	422.50	422.50
			Ribarroja	66.99	66.99	0.00	0.00	76%	76%	66.99	66.99
	Only Ribarroja and Rialb	0	Mequinenza	111.27	114.80	2.51	0.03	61%	74%	112.29	114.77
			Rialb	411.74	422.33	1.10	1.53	48%	75%	421.23	420.80
			Ribarroja	62.41	66.92	0.47	0.66	47%	76%	66.45	66.26

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Long-term	Monthly	Fails	Reservoir	Minimum Level	Average Level	Standard Error (SE)	Unforeseen Deviation (UD)	Minimum Volume%	Average Volume%	U_i (SE)	U_i^* (UD)
Only Ribarroja and Rialb	None	28	Mequinenza	115.49	115.49	0.00	0.00	76%	76%	115.49	115.49
			Rialb	415.00	420.71	5.97	2.14	55%	72%	414.74	418.57
			Ribarroja	64.10	65.99	1.85	0.01	57%	70%	64.14	65.99
	All reservoirs	0	Mequinenza	113.90	115.46	0.18	0.26	70%	76%	115.28	115.20
			Rialb	411.19	420.59	5.97	2.47	46%	71%	414.62	418.12
			Ribarroja	63.06	65.94	1.84	0.35	51%	70%	64.11	65.59
	Only Mequinenza	0	Mequinenza	112.19	115.42	0.37	0.53	64%	76%	115.05	114.89
			Rialb	415.00	420.71	5.97	2.14	55%	72%	414.74	418.57
			Ribarroja	64.10	65.99	1.85	0.01	57%	70%	64.14	65.99
	Only Ribarroja and Rialb	0	Mequinenza	115.49	115.49	0.00	0.00	76%	76%	115.49	115.49
			Rialb	403.77	420.46	6.05	3.09	32%	71%	414.42	417.37
			Ribarroja	61.88	65.89	1.86	0.76	44%	69%	64.03	65.13
None	None	**62 (CF)**	Mequinenza	115.49	115.49	0.00	0.00	76%	76%	115.49	115.49
			Rialb	422.50	422.50	0.00	0.00	76%	76%	422.50	422.50
			Ribarroja	66.99	66.99	0.00	0.00	76%	76%	66.99	66.99
	All reservoirs	0	Mequinenza	113.67	115.42	0.25	0.35	69%	76%	115.17	115.07
			Rialb	416.27	422.27	0.86	1.17	58%	75%	421.42	421.10
			Ribarroja	64.43	66.90	0.35	0.48	59%	76%	66.54	66.41
	Only Mequinenza	0	Mequinenza	111.70	115.35	0.52	0.71	62%	75%	114.83	114.64
			Rialb	422.50	422.50	0.00	0.00	76%	76%	422.50	422.50
			Ribarroja	66.99	66.99	0.00	0.00	76%	76%	66.99	66.99
	Only Ribarroja and Rialb	0	Mequinenza	115.49	115.49	0.00	0.00	76%	76%	115.49	115.49
			Rialb	408.84	422.02	1.81	2.49	41%	74%	420.21	419.53
			Ribarroja	61.21	66.79	0.77	1.06	41%	75%	66.01	65.72

Note: Levels are given in meters above sea level (m.a.s.l.). When no reservoir assumes any regulation, the scenario depicted is the same as CF in Table 3
Source: Own work.

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5. Insights from game theory

According to Gura and Maschler (2008), "Game theory is a relatively young branch of mathematics that goes back to the publication of *Theory of Games and Economic Behavior* by John von Neumann and Oskar Morgenstern in 1944. Game theory undertakes to build mathematical models and draw conclusions from these models in connection with interactive decision-making: situations in which a group of people not necessarily sharing the same interests are required to make a decision". Moreover, any game is defined by four basic elements, namely: players, rules governing play, strategies for each player, and payoffs or utilities associated with the possible outcomes obtained from the strategies applied.

Game theory is widely used in economics because almost any economic process (or conflict) can be modelled as a game with players, rules, strategies and utilities, allowing researchers to identify and assess the different outcomes which arise from players' strategic behaviour, and then to establish the best allocations. In this work, we use non-cooperative and bargaining games to evaluate and compare the actual management of environmental flows on the final stretch of the Ebro River Basin and outcomes from the management alternatives described above.

We analyse the water conflict in terms of a game between two players, on the one hand, Mequinenza reservoir, and on the other, the duo formed by Rialb and Ribarroja reservoirs. The latter plays a less relevant role in the conflict in view both of its small capacity and of its geographical location (see Figure 1), and its evolution is strongly dependent on the strategies deployed by Mequinenza and Rialb. Both Rialb and Ribarroja are in Catalonia, making both reservoirs potentially members of a Catalan coalition. For all these reasons and for the sake of simplicity, we will from now on treat the conflicts as a two-player game and assume that Rialb and Ribarroja always apply the same strategies.

According to game theory, a conflict can be addressed in any one of three ways: 1) non-cooperative games (without negotiation or cooperation), 2) bargaining games (without cooperation), and 3) cooperative games. These three types of games represent different institutional scenarios (rules) or forms of interaction between agents.

In *non-cooperative games*, each agent seeks the best outcome for himself, regardless of any gain or loss for other players. The typical solution is the non-cooperative Nash equilibrium (Nash, 1951). In *bargaining games*, each player only considers his own benefit, but all are willing to engage in negotiation in order to increase their payoff (Nash, 1950). In a bargaining game framework, then, an efficient (Pareto optimum) solution for all players is needed to reach agreement. The Nash (Nash, 1950), and Kalai-Smorodinsky solutions (Kalai and Smorodinsky, 1975) are the most common.

Finally, the touchstone in *cooperative games* is joint benefit, although the possible allotment of outcomes is treated as secondary. Under the assumption of rationality, nobody should receive less from allocation than they could obtain individually. These games are usually solved by seeking a nucleus or nucleolus, or by means of Shapley Allotments (Shapley, 1988). The robustness of the equilibrium reached can be analysed using indexes developed for this purpose (Dinar and Howitt, 1997). We have not considered cooperative games in view of the social, economic and institutional context of the River Ebro, even though such games are generally applied in water-related scenarios.

5. 1 Defining utility functions

The average water level and volume are good indicators of a reservoir's functioning, since both variables capture the same information and utility functions based on them provide similar results. We can, then, safely assume that adverse outcomes or losses for the agents increase when level values fall. On the other hand, fluctuations in water levels generally have a negative impact on growth and development. Moreover, they complicate tourist and residential development and a high variance can leave reserves at extremely low levels and cause irreversible impacts on flora and fauna. Hence, the standard errors for the levels observed provide a sure measure of these last adverse effects. In this context, a first type of utility functions for each reservoir was calculated by subtracting the standard error from the average level for the total period of our simulations (see Equation 3 below).

In order to avoid penalizing long-term regulation, we also develop other utility functions using the unforeseen deviation instead of standard error. These utility functions are designed to reflect the fact that the real damage to stakeholders can be calculated in terms of their expectations, if the agents know the expected level of each reservoir in advance. Unforeseen deviation is defined in a similar way to standard error using the expected level instead of the average level (see Equation 4). The qualitative results obtained from both utility functions do not differ significantly, but (4) opens the way for future research incorporating more flexible scenarios.

Utility function with standard errors:

$$U_i = \bar{x}_{i,600} - \sigma_{i,600} \quad (3)$$

Utility function with unforeseen deviations:

$$U_i^* = \bar{x}_{i,600} - \sqrt{\frac{1}{600}\sum_{j=1}^{600}\left(x_{i,j}^e - x_{i,j}\right)^2} = \bar{x}_{i,600} - \sigma_{i,600}^{UD} \quad (4)$$

Where U_i and U_i^* represent the utilities for reservoir i obtained from our simulations, $\bar{x}_{i,600}$ is the average level for 600 months, from 1964 to 2014, and $\sigma_{i,600}$ is the standard error in these months; $x_{i,j}^e$ represents the fixed level in month j for reservoir i according to planned long-term regulation, see Table SI4 in the SI; $x_{i,j}$ represents the observed value for reservoir i in month j according to the simulation; and $\sigma_{i,600}^{UD}$ is the unforeseen deviation.

The values of our utility functions are shown in Table 4 and also in Tables 5-8. Table 4, presented in the previous section, shows the standard error and unforeseen deviation, respectively, in the seventh and eighth columns. The last two columns represent the two utility levels, U_i and U_i^*.

As shown in Table 4 and as expected, the maximum utility U_i for Mequinenza, 115.49 m.a.s.l., is reached in four situations, when the reservoir does not take on either long-term or monthly regulation. This happens regardless of what Rialb and Ribarroja do. The lowest utilities are found when Mequinenza assumes both types of regulation alone (112.26 for U_i and 114.33 for U_i^*), without assistance from Rialb or Ribarroja. In this case, the minimum level of reserves drops to 55% of total capacity. This level is environmentally unacceptable, though it is unfortunately the current institutional reality.

5. 2 Non-cooperative games

In games of this type, players seek only to optimize their own utility. The values are shown in Table 4 and also in the payoff matrixes for Mequinenza and Rialb shown in Tables 5-8. Tables 5 and 7 show the payoff matrixes for the utility function with standard error U_i, while Tables 6 and 8 reflect those associated with U_i^*. The four tables (5-8) present four pure strategies or alternatives for each player based on the two basic planning alternatives discussed above, namely doing nothing (n), long-term regulation (L) only, monthly regulation only (M), and the combined strategy of long-term and monthly regulation (LM).

No conditions are imposed in Tables 5 and 6, assuming also that any alternative (n, L, M, or LM) is viable for any player. Therefore, the environmental flows will not be fulfilled if, for example, both player choose the strategy doing nothing (*n*). In both tables, a surprising first result is that the two alternatives which include long-term planning (L and LM) are strictly dominated by each of the other two (n and M) for both players. This also shows that long-term planning, according to the data for the whole period of 50 years used in the case study, is not a good alternative although it does reduce the number of failures. Hence, short-term and monthly planning without long-term planning is always better, revealing the need for an Ebro Basin Authority with "permanent" responsibility on water management.

Table 5. Non-cooperative Game - Mequinenza vs Rialb – Average level minus SE

U		Rialb			
		n	L	M	LM
Mequinenza	n	**115.49; 422.50**	**115.49**; 414.74	**115.49**; 420.21	**115.49**; 414.42
	L	112.29; **422.50**	112.75; 420.44	112.29; 421.23	112.75; 420.01
	M	114.83; **422.50**	115.05; 414.74	115.17; 421.42	115.28; 414.62
	LM	112.26; **422.50**	112.69; 420.44	112.28; 421.90	112.72; 420.30

Table 6. Non-cooperative Game – Mequinenza vs Rialb -Average level minus UD

U^*		Rialb			
		n	L	M	LM
Mequinenza	n	**115.49; 422.50**	**115.49**; 418.57	**115.49**; 419.53	**115.49**; 417.37
	L	114.77; **422.50**	115.31; 422.24	114.77; 420.80	115.31; 420.83
	M	114.64; **422.50**	114.89; 418.57	115.07; 421.10	115.20; 418.12
	LM	114.33; **422.50**	114.96; 422.24	114.57; 421.69	115.17; 421.62

Table 7. Non-cooperative Game - Mequinenza vs Rialb – Average level minus SE - feasible points

U		Rialb			
		n	L	M	LM
Mequinenza	n	-	-	**115.49; 420.21**	**115.49**; 414.42
	L	-	-	112.29; **421.23**	112.75; 420.01
	M	**114.83; 422.50**	**115.05**; 414.74	115.17; 421.42	115.28; 414.62
	LM	112.26; **422.50**	112.69; 420.44	112.28; 421.90	112.72; 420.30

Table 8. Non-cooperative Game – Mequinenza vs Rialb – Average level minus UD - feasible points

U^*		Rialb			
		n	L	M	LM
Mequinenza	n	-	-	**115.49; 419.53**	**115.49**; 417.37
	L	-	-	114.77; 420.80	115.31; **420.83**
	M	**114.64; 422.50**	114.89; 418.57	115.07; 421.10	115.20; 418.12
	LM	114.33; **422.50**	**114.96**; 422.24	114.57; 421.69	115.17; 421.62

The Nash equilibrium in Tables 5 and 6, is the solution in which no player takes on responsibility for management. This implies another relevant finding, namely that a non-cooperative approach would not assure compliance with environmental flows without an institutional framework to enforce environmental requirements and limit private economic uses.

Since such an authority does in fact exist in CHE, we can advance in the analysis by assigning zero values to the crossover strategies underlying non-compliance with environmental flows in order to evaluate the game outcomes by imposing compliance, see Tables 7 and 8. Once again, the M strategy of both players strictly dominates their L and LM strategies in both payoff matrixes, making monthly planning better than long-term planning and again revealing the need for an Authority with "permanent" responsibility on water management. The game using standard errors (U_i), reflected in Table 7, has three Nash equilibriums. Two of them, M-n and n-M are pure strategies, and the other is a mixed strategy. The mixed strategy equilibrium implies a 99.74% probability that Mequinenza would contribute to monthly regulation (M), while there would be a 98.72% probability that Rialb would do so (M). Both figures are very close to one, so we can identify the third Nash equilibrium as one where all reservoirs play a part in monthly regulation, a collaborative solution close to the alternative M-M. By contrast, the solutions M-n and n-M are obtained in the absence of cooperation. We may recall here that M-n represents the current situation, where Mequinenza Reservoir alone shoulders the burden of regulatory environmental flows, dropping the minimum level of reserves to 62% of total capacity, which is environmentally unacceptable. In n-M we have a similar situation, Rialb and Ribarroja alone shoulder the regulation but reserves at both reservoirs fall to a minimum level of 41%, which again is environmentally unacceptable. In other words, the only solution compatible both with environmental water requirements and current economic uses is the cooperative solution between the three reservoirs. The same conclusion is reached using the utility function U_i^* and its unforeseen deviations, as may easily been seen from Table 8.

These three equilibria also point to another relevant social and institutional conclusion concerning the conflict with Catalonia. The two Catalan reservoirs, Rialb plus Ribarroja, could assure the fulfilment of regulated EF either by themselves (strategy n-M) or in partnership (mixed strategy). Thus, Catalonia would not need an agreement with the rest of Spain to fulfil the Ebro Delta EF, although the environmental cost to both reservoirs would be enormous.

This game can be also analysed from a "leader-follower" standpoint, where the leader would guide the game to the Nash Equilibrium that best suits it. Given the privileged geographical situation of Mequinenza reservoir and its size, the leader-follower Nash equilibrium would be (n-M), which would allow Mequinenza to maximize its level and utility. This is also the expected equilibrium if there is no cooperation between Catalonia and the rest of Spain, though it would be a bad solution as mentioned above.

5.3 Bargaining games

Bargaining games represent another potential application of game theory to the search for and evaluation of equilibrium, especially when utility transfers between players are possible. We do not assume any utility transfer between players in our game for the sake of simplicity, although in the actual economy there is indeed room for utility transfers between the players through investment in irrigation and infrastructure by the Spanish government or by tweaking the water use rights granted by the Ebro Basin Authority.

Furthermore, bargaining games allow analysis based on variations in bargaining power, allowing us to lay bare the institutional framework and power ratios underlying the current management of environmental flows. Policymakers might decide to assign different levels of bargaining power for a variety of reasons. For instance, greater bargaining power associated with Mequinenza could compensate the district's population for having shouldered the burden of environmental stewardship until now. On the other hand, greater bargaining power associated with Ribarroja or Rialb could represent a framework within which to raise the bargaining power of the smallest reservoir's users (farmers, villages, etc.).

The *status quo* (points of disagreement or payments which players expect to receive if they do not reach an agreement) is a basic element of bargaining games, and it usually reflects different institutional frameworks. We show results for two such possible frameworks. In the first we define the *status quo* as the utility associated with 50% of reservoir capacity (i.e. the level used to optimize long-term regulation), and in the second we take the worst feasible alternative for each player, i.e. the utility level that each player would obtain if it had to shoulder the burden of environmental flow management entirely on its own.

Under these conditions, the bargaining solutions of the game are obtained according to Nash (1950) through optimization of the product of utility gains. Specifically, the problem is solved for U_i as follows:

$$\left[Max \prod_{i=1}^{2} (U_i - q_i^o)^{\alpha_i} = Max\, S[(U_i)] \right] \quad (5)$$
$$(U_i) \in Bargaining\ set$$

Where (q_i^o) is the *status quo* chosen, α_i the bargaining power of player i, and $S[(U_i)]$ the utility isoquants associated with (U_i), and the bargaining set:

$$\{(U_i)|U_i \in convex\ hull\ of\ points\ from\ Table\ 7;\ U_i \geq q_i^o\ ;\ and\ Pareto\ optimum\} \quad (6)$$

We have a similar equation for U_i^*, which is estimated based on the points from Table 8.

Table 9 shows the Nash Bargaining Equilibrium for both *status quo* alternatives using the two utility functions and various bargaining powers. Similar information is shown in Figures 3-6, where we may also observe the optimum isoquants for three pairs of bargaining powers and the *status quo* point where the axes cross. Figures 3 and 4 represent the bargaining game using standard error utility functions (U), and Figures 5 and 6 using unforeseen deviations functions (U^*).

As shown in Table 9 and in Figures 3-6, the Nash bargaining equilibrium differs depending on the type of utility function (U or U^*) and the *status quo* used. When the utility associated with 50% water reserves is taken as the *status quo*, bargaining power becomes critical to the Nash Equilibrium. If the bargaining power of Rialb reservoir is higher than or equal to that of Mequinenza reservoir (cases 1-1, 1-2 and 1-3), the latter will take on full responsibility for management when the utility function used is U and the solution is M-n, and it also will shoulder the lion's share of the burden in the case of utility U^* with solutions M-n and LM-L. By contrast, if Mequinenza reservoir has significantly higher bargaining power (case 3-1), both players implement the Nash bargaining solution together so that cooperation is necessary, and the solution is close to M-M for the utility U, and to LM-LM for U^*. In other words, assigning increased bargaining power to Mequinenza shifts the game towards a cooperative equilibrium.

Fixing the *status quo* as the worst feasible alternative always leads to a cooperative solution. This *status quo* is too much for Rialb, forcing it to play a role that is similar to assigning higher bargaining power to Mequinenza, which results in a more favourable equilibrium for the latter than in the previous case for both utility functions. Assuming equal bargaining power in this case, the results are M-M for U and LM-LM for U^*.

Table 9. Bargaining Game Theory Equilibria, Mequinenza Reservoir versus Rialb Reservoir

Bargaining Power	Status Quo	Equilibria when U		Equilibria when U^*	
3-1	50% of capacity	115.168 - 421.416	M-M	115.167 - 421.619	LM-LM
2-1		114.827 - 422.50	M-n	114.96 - 422.237	LM-L
1-1		114.827 - 422.50	M-n	114.96 - 422.237	LM-L
1-2		114.827 - 422.50	M-n	114.635 - 422.50	M-n
1-3		114.827 - 422.50	M-n	114.635 - 422.50	M-n
3-1	Worst feasible alternative	115.324 - 420.83	Mixed equilibrium	115.308 - 420.828	L-LM
2-1		115.269 - 421.037	Mixed equilibrium	115.237 - 421.227	Mixed equilibrium
1-1		115.168 - 421.416	M-M	115.167 - 421.619	LM-LM
1-2		115.067 - 421.737	Mixed equilibrium	115.046 - 421.981	Mixed equilibrium
1-3		115.007 - 421.928	Mixed equilibrium	114.96 - 422.237	LM-L

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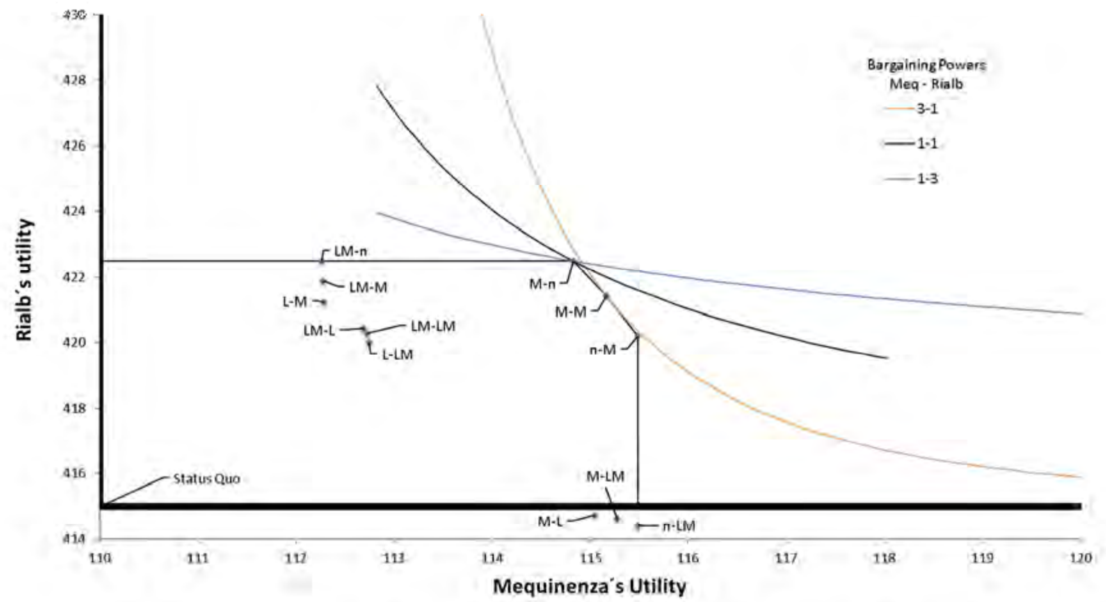

Figure 3. Mequinenza vs Rialb – (U) - status quo at 50% capacity.

Note for figures 3-6: The black isoquant depicts equal bargaining power, while the orange isoquant depicts greater bargaining power (3/1) for Mequinenza and the blue one for Rialb

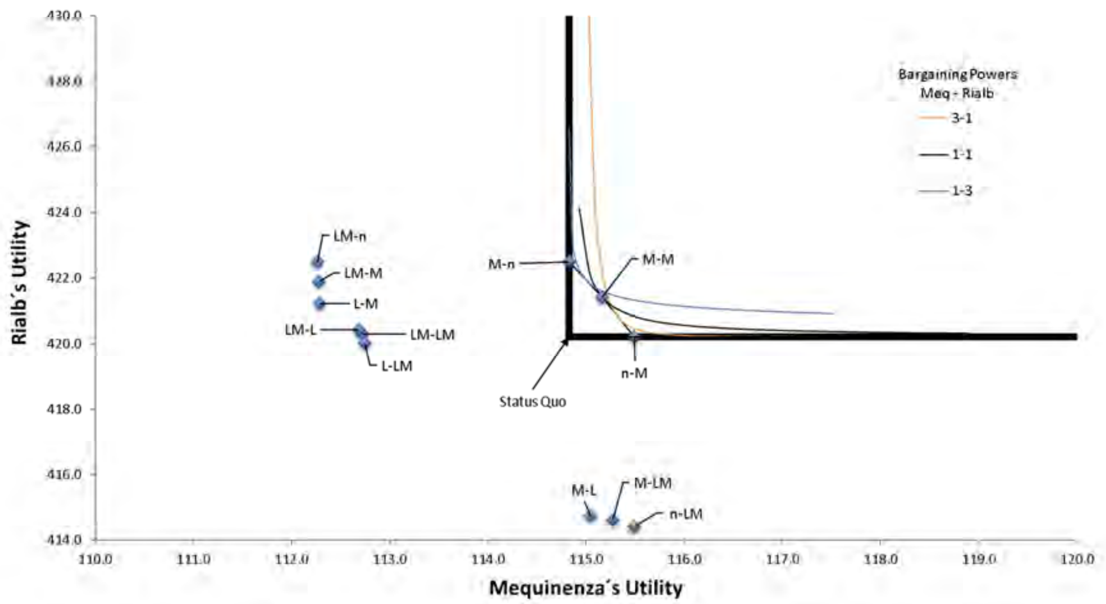

Figure 4. - Mequinenza vs Rialb – (U) - status quo at worst feasible alternative (114.83-420.21)

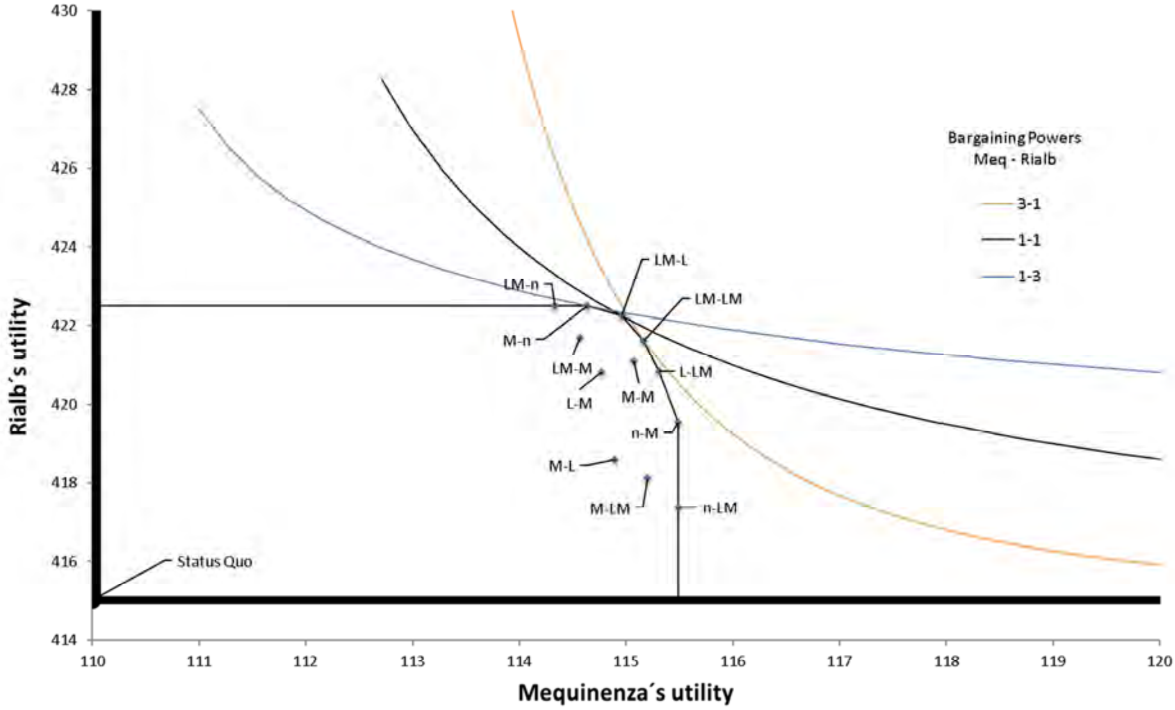

Figure 5. Mequinenza vs Rialb – (U^*) - status quo at 50% capacity

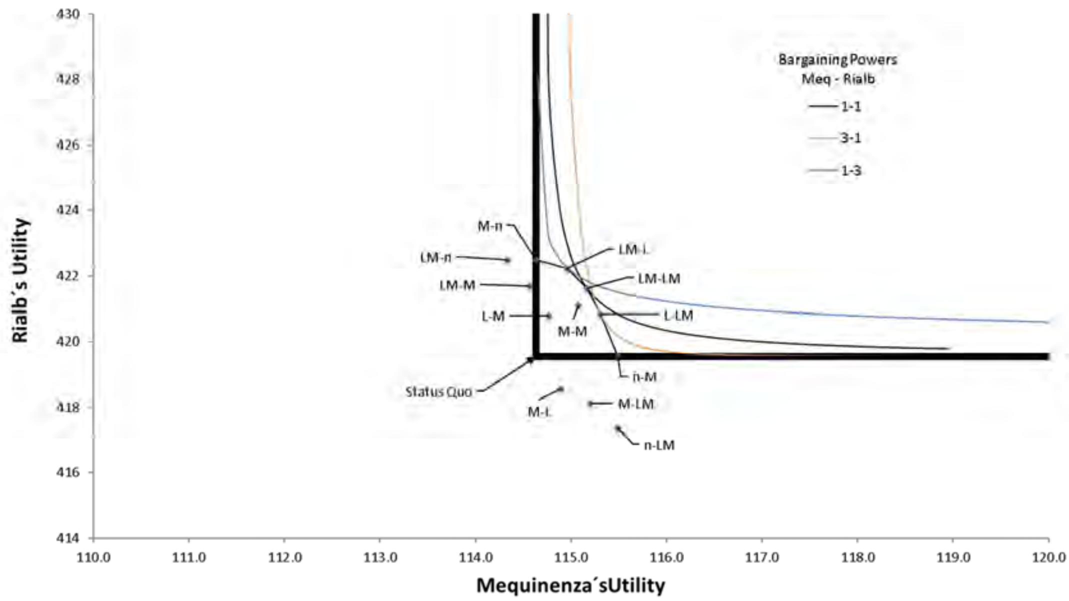

Figure 6. - Mequinenza vs Rialb – (U^*) - status quo at worst feasible alternative (114.63-419.53)

6. Conclusions and discussion

The allocation of natural resources has been widely studied by economists. In this paper, we consider water uses and the alternative ways of avoiding possible conflict between economic agents and the environment, focusing our analysis mainly on water use in the final stretch of the Ebro River (Spain) in the period 1964-2014. We have developed a water management model to simulate and evaluate different flow management hypotheses, and we have also combined the results obtained from the simulations with non-cooperative and bargaining games for getting the best water allocations. We seek to answer three key questions: (i) Are current and regulated environmental flows for the Ebro Delta (a Biosphere Reserve) acceptable? (ii) Are the current economic use (mainly irrigation and hydroelectric generating) compatible with environmental requirements? (iii) Is there a fairer and more cooperative alternative for water management in the area than the current one?

The model is used to analyse four scenarios (CF, HEF, LFCC and HEF&LFCC) and two types of water planning (long-term regulation and monthly regulation), and eventually leading on to the examination of findings using non-cooperative and bargaining games.

In the CF scenario we assume no regulation (which is similar to assuming that there are no dams) and the first finding from this simulation is conclusive: compliance with the current EF in the River Delta would be almost impossible without infrastructure and dams. Hence, reservoir and dam management is necessary if we are to maintain the current economic uses with no or little effect on the environment. In other words, something similar to the Ebro Basin Authority (CHE) is necessary. A further conclusion from this scenario is that uses in the Ebro Basin are close their limits. This is very important in view the declining trend in Ebro Basin flows observed in recent decades and expected climate change impacts.

In scenario HEF we assume a 10% increase in current Ebro Delta EF and no regulation. The simulations reveal an increment in the failed months (80 versus 62 in the previous scenario). This demonstrates the difficulty of meeting the ever increasing demands made by the Catalan regional government in recent years. In scenario LFCC we simulate a 20% fall in inflows, to reflect the possible effects of climate change. Again, the failed months rise (150 months versus 62 in CF). Both of these scenarios once again confirm that water uses are already bumping up against their limits, and that an Ebro Basin Authority is needed, not to mention an improvement in water management policies.

The current water management policy deployed by the Ebro Basin Authority (CHE) is based on additional daily and/or monthly flows from Mequinenza reservoir, which ensures the water supply for economic activities while at the same time allowing compliance with environmental flows, except in occasional cases arising mostly in times of extreme drought. This is directly confirmed by the data and by our simulations. However, we consider that the current management structure is highly questionable as regulation is handled by Mequinenza alone, sometimes leaving the reservoir not just below the acceptable environmental level of 110 meters (representing 50% of capacity) but even below the level where irrigation water intakes are situated (105 meters above sea level), resulting in high financial, opportunity and environmental costs for the surrounding area, see Almazán-Gómez and Sánchez-Chóliz (2016).

For these reasons, we have evaluated two alternative water management strategies using our model. The first is *long-term regulation*, and it consists of establishing optimal monthly levels to be repeated each year. The second is *monthly regulation*, which requires occasional targeted discharges to fulfil EF requirements. Our results show that *long-term regulation* is useful because it reduces the number of months in which environmental flows cannot be fulfilled, but it is not enough for a full compliance with EFs. Hence, monthly regulation (additional daily or monthly discharges) is needed to comply with regulatory EFs in the Ebro Delta. Again, the results suggest that an institutional framework and a river basin authority are necessary to ensure that environmental and economic water demands in the area are met. As a final significant result, it would appear that compliance with Ebro Delta environmental flows does not depend exclusively on the reserves of Mequinenza reservoir. There are alternatives to the current management strategy, in which the burden is shouldered by Mequinenza alone, so that Rialb and Ribarroja could take part in flow management or even assume stewardship entirely. In other words, cooperative management strategies are viable.

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We then used game theory to evaluate management strategy alternatives, designing utility functions based on the simulation results for each alternative and reservoir. Non-cooperative and bargaining games each with its own *status quo* and bargaining power parameters are used.

By analysing non-cooperative games, we have been able to ascertain that the current management structure (M-n), where Mequinenza reservoir shoulders the full burden of regulation, is a Nash Equilibrium, confirming its "rationality" under the current institutional rules, which accept as "normal" a high degree of environmental damage for Mequinenza reservoir and its surrounding district. Another Nash equilibrium is n-M, in which Rialb and Ribarroja take on the burden alone, again at a high environmental cost, making this too a bad alternative. However, these games have a third, mixed-strategy Nash Equilibrium supporting a more equitable and collaborative alternative. This is important because it confirms the existence of a technical basis for collaboration and for sharing the burden of monthly regulation together.

Bargaining games are a standard analytical tool when different Nash equilibria exist, because they allow us to select between efficient or Pareto-optimal alternatives. This type of analysis can be refined by changing the *status quo* (which we may associate with different institutional situations) and negotiating powers of each player. We have used two different parameters for the *statu quo*, five bargaining power pairs and two utility functions.

The solutions obtained from this analysis are crystal clear. Although the current management criteria represent a solution if Mequinenza's bargaining power is low, cooperative solutions become more probable the greater the negotiating power assigned to Mequinenza, or the greater the no agreement cost for Rialb and Ribarroja. This of course casts serious doubt on the fairness of the current institutional water management arrangements for the lower stretch of the Ebro River.

To sum up, let us consider the answers to our three key questions. First, increasing current regulated flows would be problematic in the medium and long term, especially considering the potential impacts of climate change and the difficulty of removing existing, vested water use rights in the Ebro Basin. Second, both economic (irrigation and hydroelectric generating) and environmental uses are viable assuming current EFs. Third and finally, fairer cooperative solutions do exist, which involve sharing regulatory burdens and relieving the pressure on the Mequinenza area. Moreover, these solutions could promote and increase irrigation in the area by releasing draw-offs for other uses from this reservoir.

The methodology employed in this study represents merely the first step in a complex analysis that could easily be extended to the whole Ebro River Basin and indeed to other river basins in Spain and elsewhere. This paper merely provides a baseline for the study of socio-economic effects throughout the Ebro Basin and a point of departure for economic policy proposals.

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