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Tradeoffs in river restoration: Flushing flows vs. hydropower generation in the Lower Ebro River, Spain

Carlos M. Gómez [a,b], C. Dionisio Pérez-Blanco [a,b,*], Ramon J. Batalla [c,d,e]

[a] University of Alcalá (UAH), Plaza de la Victoria 2, 28802 Alcalá de Henares, Madrid, Spain
[b] Madrid Institute for Advanced Studies in Water Technologies (IMDEA-Water), C/Punto Net, 4, 2° piso, Edificio ZYE, Parque Científico Tecnológico de la Universidad de Alcalá, 28805 Alcalá de Henares, Madrid, Spain
[c] Department of Environment and Soil Sciences, University of Lleida, E-25198 Lleida, Catalonia, Spain
[d] Forest Science Centre of Catalonia, E-25280 Solsona, Catalonia, Spain
[e] Catalan Institute for Water Research, H2O Building, E-17003, Girona, Catalonia, Spain

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SUMMARY

Although the effectiveness of flushing floods in restoring basic environmental functions in highly engineered rivers has been extensively tested, the opportunity cost is still considered to represent an important limitation to putting these actions into practice. In this paper, we present a two-stage method for the assessment of the opportunity cost of the periodical release of flushing flows in the lower reaches of rivers with regimes that are basically controlled by a series of dams equipped with hydropower generation facilities. The methodology is applied to the Lower Ebro River in Spain. The results show that the cost of the reduced power generation resulting from the implementation of flushing floods is lower than the observed willingness to pay for river restoration programmes.

1. Introduction

Water is an economic asset necessary to sustaining life, the environment and the production of many valuable goods and services and should be managed accordingly. However, the prevailing paradigm considers water demand to be exogenous, and water policy, consequently, has traditionally focused on guaranteeing the supply of water services at affordable prices. As a result, during the last decades population growth and the improvement of living standards brought about by development have increased the pressures on water resources. The negative environmental effects stemming from this paradigm are visible for instance in the case of the European and North American rivers, where the need to satisfy a continuously growing demand for water and river services has resulted in increased water abstractions and polluted discharges along with gravel mining, canalisation, and successive modifications in river morphologies (e.g., Furse et al., 2006; Zawiejska and Wyzga, 2010; Batalla and Vericat, 2009).

Consequently, restoration of river ecosystems has become a priority for water management in the developed world, especially in the stressed lower reaches of its rivers (Gupta and Bravard, 2010; EC, 2000). However, restoration is often obtained at the cost of impairing the ability of water infrastructures to provide valuable socioeconomic goods and services, such as hydropower (Bednarek and Hart, 2005; Palmieri et al., 2001; Robinson and Uehlinger, 2003). There is thus a considerable interest in learning how to balance river restoration benefits with the production of goods and services provided by water infrastructures.

As a result of this interest, significant effort in scientific research has recently been mobilised in two important directions. Considerable progress has been made in the assessment of current ecological status and trends and in the design of effective technical alternatives to restoring some basic environmental functions of rivers. In particular, emerging research in biology and ecological engineering (e.g., Granata and Zika, 2007) shows that dams and other infrastructures that alter river systems can also be used as tools to reproduce artificially a portion of the functions performed in the past by the natural system. For instance, modifying the rules of hydropower dam operation to guarantee the periodic release of properly designed maintenance flows (namely, flushing flows) may effectively replace the role performed in the past by the natural floods characteristic of many rivers, which served to maintain the structure and functions of the river ecosystem (see Hueftle and Stevens, 2002; Vinson, 2001; Kondolf and Wilcock, 1996). Social sciences have also provided methods and results for the valuation of the economic and social benefits of potential improvements in the capacity of river systems to increase the quantity and range of those environmental services that might result from a successful restoration of river systems (such as

* Corresponding author at: University of Alcalá (UAH), Plaza de la Victoria 2, 28802 Alcalá de Henares, Madrid, Spain. Tel.: +34 91 830 59 62; fax: +34 91 830 59 61.

E-mail address: dionisio.perez@imdea.org (C.D. Pérez-Blanco).

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recreation opportunities, biodiversity support, health services, water security and flood control) (see, for example, Hitzhusen, 2007; Turner et al., 2003 and Gupta and Bravard, 2010; CSIRO, 2012). However, there is still little research on the costs of practically applying the available options to improve rivers' ecology, which makes the opportunity cost of water the missing element for the assessment of the policy options at hand.

Information on opportunity costs plays a critical role in the evaluation of river restoration alternatives for a series of reasons: to find the most cost-effective way to improve the river environment and thus minimise the impact over marketable water services, to judge whether the associated cost is lower than the benefits expected from the improvement of the water environment (and to assess later whether the proposed measures are justified in the light of cost benefit criteria), to provide the critical information to assess what would, for example, be the minimum compensation demanded by water users for voluntarily adapting the use of the resource to certain new requirements and to know the real cost of harmonising the provision of water services and the improvement and protection of the water environment.

This paper aims to help bridge this information gap. The paper presents a model for the evaluation of the opportunity costs of implementing a given flushing flow programme in an area where the flow regime is driven by the operation of a hydropower facility. In such a situation, the requirement to release the flushing flow means that for certain precise periods of time, the outflow of water does not depend on the profit maximising criteria used by the hydropower plant (baseline scenario) but rather on an operating constraint imposed by an environmental authority (counterfactual flushing-flow scenario). The opportunity cost of such measures is therefore represented by the monetary losses of the concerned commercial activity, namely, hydropower. The overall question we want to answer can be presented as determining a financial value for the compensation required by a hydropower operator to voluntarily accept a predetermined programme of periodical artificial releases. The model is illustrated with an application to the Lower Ebro River, Spain.

2. The Lower Ebro River: river diagnosis and the need of flushing flows

The Lower Ebro River is located in the northeast of Spain and comprises the area located between the Mequinenza–Ribarroja–Flix Dam Complex (hereafter MRFDC) and the outlet of the river to the Mediterranean Sea (see Fig. 1). Water demand from agriculture is significant (1.200 million cubic meters/year, i.e., 90% of the total water demand), and runoff has been reduced by more than 20% as a result of increasing pressures from upstream and long-term changes in land use (i.e., afforestation). However, flows are still relatively abundant, and droughts are rare (ERBA, 2007). The main environmental concern in the area is related to the impoverished ecological status that resulted from the alteration of the river's hydrology and, subsequently, the channel morphology after the construction of the MRFDC (see Table 1).

The large Mequinenza and Ribarroja dams built in the 1960s substantially modified the flow regime of the Lower Ebro. Among other hydrological components, flood magnitude and frequency have been altered. Of particular interest for the river's ecological functioning is the 25% reduction, on average, of the relatively frequent floods (i.e., those with a return interval between 2 and 25 years) (Batalla et al., 2004). Although the river still experiences natural floods, and the impact of regulation is much smaller than that found in comparable large rivers, such as, for instance, the Sacramento and the San Joaquin Rivers in California (Kondolf and Batalla, 2005), the river's physical and environmental conditions have changed notably in the last decades (e.g., Batalla et al., 2006; Vericat and Batalla, 2006; Vericat et al., 2006; Batalla and Vericat, 2009). The main dam induced changes can be summarised as follows:

- Reduction of flood frequency and magnitude; floods provide the energy for maintaining an active river channel morphology, and this reduction has led to the loss of formerly sedimentary active areas, the encroachment of riparian vegetation and the narrowing of the channel.
- Reduction of the river's sediment load, which implies the erosion of the gravel fractions in the channel with no replacement from upstream and simultaneous riverbed armouring during small frequent floods and during high flow periods.
- Alteration of the river's ecology, as a compound effect of impoundment, exemplified by the low frequency of bed moving floods, slow moving waters, deficit of fine sediment, high temperatures and excess nutrient load. These combined alterations create a new functioning in the river ecosystem with consequences regarding the river's ability to provide key environmental services.

This new set of environmental conditions, together with similar changes in the upstream main tributaries, appears to explain the uncontrolled proliferation of macrophytes[1] in the Lower Ebro River channel (e.g., Goes, 2002; Palau et al., 2004). Macrophytes threaten river infrastructures, increasing operating costs, reducing the productivity of power-generating plants and water-pumping devices and reducing the ability of the river to provide navigation and recreation services. Competition for space and resources resulting from the stabilisation of dense macrophyte stands also affects the biology of the river ecosystem in many different ways. Macrophyte stands limit the access to microhabitats that are important for the growth and survival of juvenile fish, and the decomposition of growing organic matter depletes the water of its oxygen. Macrophytes communities also enhance flow resistance, thus exacerbating the reduction in flow velocity and trapping an important portion of fine sediment load (Batalla and Vericat, 2009).

Within this context, a considerable body of research has been devoted to the design and implementation of flushing flows as a means to improve the ecological status of the Lower Ebro River. These efforts started in 2002 following two notably dry years. These drought conditions encouraged cooperation between the hydropower operator, the water authorities and the scientific community. With the exception of two dry years in 2004 and 2005, flushing flows have been regularly performed twice a year (in autumn and spring). These flushing flows have provided opportunity to the design of such flows to increase their effectiveness, and macrophytes removal rates as high as 95% have been achieved in areas close to the dam (Batalla and Vericat, 2009). Despite the need to limit peak floods to avoid damage to riverine villages, flushing flows in the Lower Ebro are now a tested means to enhance the biological productivity of the physical habitat, to entrain and transport sediments to restore the dynamism of the river channel, to remove pollution loads and improve the water quality, to control salt intrusion and to supply sediments to the delta and the estuary.

Fig. 2 presents the standard hydrograph of the flushing flow implemented in the Lower Ebro since 2002 (for an extensive anal-

[1] Macrophytes are visible algae and other flora species that are rooted in shallow waters with vegetative parts emerging above the water surface. In lakes, macrophytes provide cover for fish and substrate for aquatic invertebrates, produce oxygen, and act as food for some fish and wildlife, therefore being a symptom of a good environmental status. However, in a river their proliferation occurs when water is stagnated and denotes a poor environmental status, having negative effects over the ecosystem and economic activities.

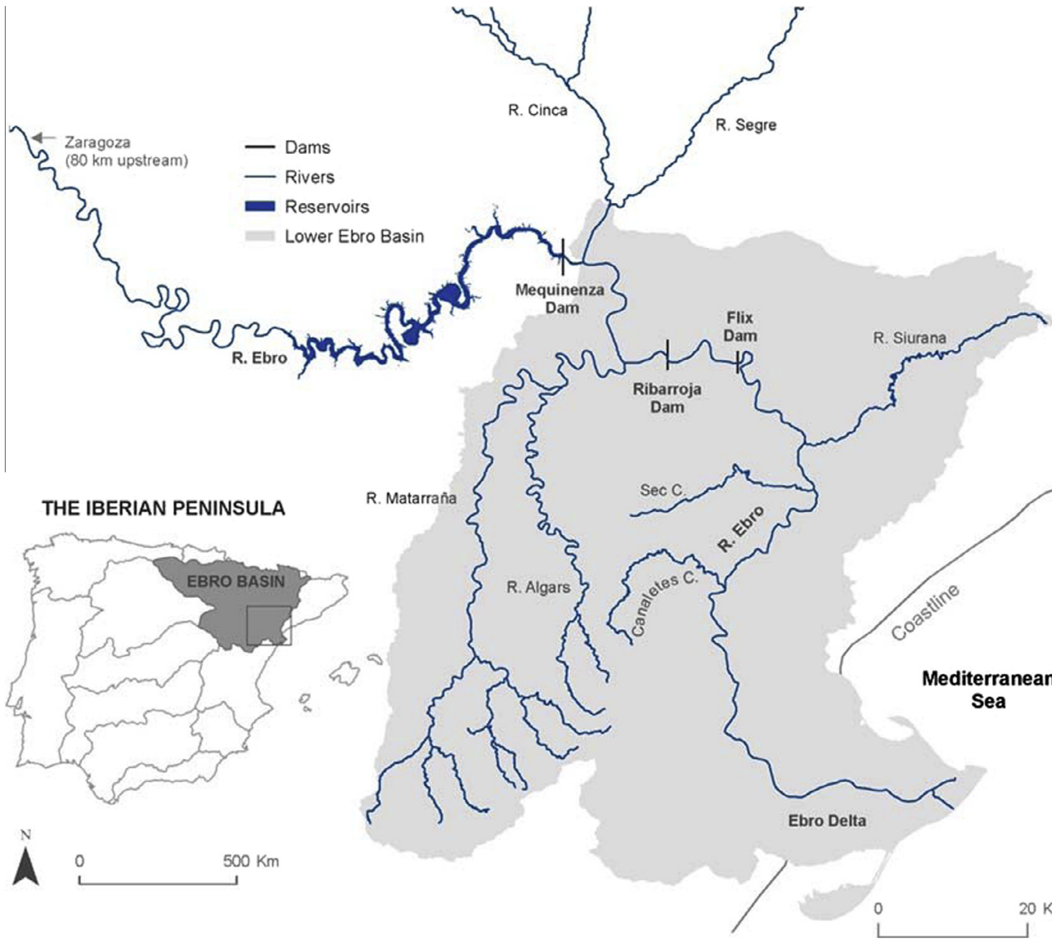

Fig. 1. Location of the River Ebro Basin in the Iberian Peninsula and detail of the Lower Ebro River. *Source*: Own elaboration from ERBA, 2012a.

Table 1
Characteristics of the Mequinenza–Ribarroja–Flix dam system.

Reservoir	Mequinenza	Ribarroja	Flix
Storage capacity (h m^3)	1530	218	5
Licensed flow (m^3/s)	760	940	400
Installed capacity (kW/h)	324	262.8	42.5
Height (m)	74	41	12.1
Efficiency	0.8	0.8	0.8
Input output ratio (m^3/kW h)	6.2	11.19	37.91

ysis of the flushing flow design and field monitoring, as well as a critical discussion on its effectiveness as a river restoration tool, see Batalla and Vericat, 2009).

3. Materials and methods

The opportunity cost of artificial flood flows in modified river reaches, where the flow regime is basically determined by the operation of hydropower facilities, can be defined as the reduction of the value of the energy produced resulting from the new environmental constraints. The assessment of this opportunity cost requires knowledge of the hydropower operator's profit maximising decision-making and how it would react to a change in the operating constraints imposed by the river basin authority. To solve this problem, we present a theoretical general model that allows the calculation of the opportunity cost of flushing flows based on the previously stated characteristics and we calibrate the general model to our particular case study in the Lower Ebro River[2].

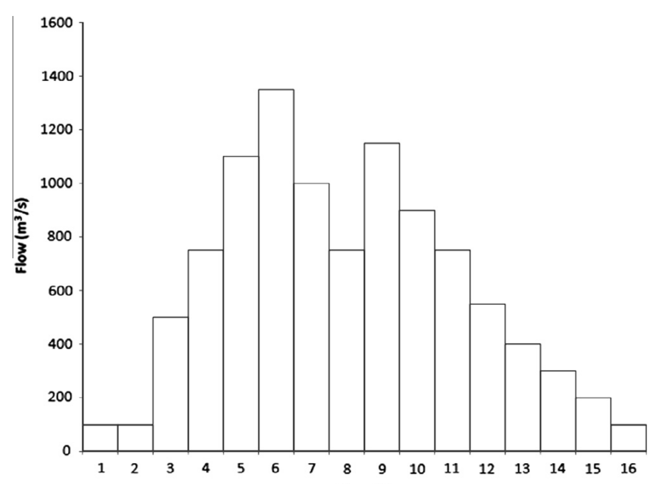

Fig. 2. Standard hydrograph of the flushing flow implemented in the Lower Ebro River since 2002. *Source*: Own elaboration.

[2] It is important to note that in the calibration stage we use econometric techniques. An analytical solution to the theoretical problem would demand accepting strong assumptions about the operator's behaviour (assuming either perfect hydrological foresight or accepting strong assumptions about the operator's risk attitude) that make preferable to deduce this solution from the decisions that the operator has taken in the past.

3.1. The basic opportunity cost evaluation model

From the hydropower operator's perspective, the dam and its associated power production facility are capital assets. At any given time, the operator decides on the flow of energy to be produced. This decision is based upon a number of variables, such as the technical characteristics of the plant, the current operating rules, the expected evolution of the amount of water stored in the reservoir and the current and the expected energy prices. From a private business perspective, these decisions aim at maximising the value of the expected flow of benefits along the entire life span of the dam. As the electricity produced cannot be stored for future selling, the hydropower operator has to make two kinds of decisions simultaneously. The first decision involves choosing how much water to release every day (x_t), and the second involves choosing how to distribute the electricity generated throughout the day (x_{tk}). Both decisions aim to maximise the flow of hydropower revenues. In what follows, we analyse each of these key production decisions:

Decision (1): the volumes of water released everyday can be represented by the following dynamic optimisation programme. For simplicity, we assume a zero discount rate:

$$\max_{x_t} \sum_{t=0}^{\infty} E[\Pi_t(x_t)] \quad (1)$$

$$z_{(t+1)} = z_t + y_t - x_t \quad (2)$$

$$\underline{z_t} \leqslant z_t \leqslant \overline{z_t} \quad (3)$$

$$\underline{x_t} \leqslant x_t \leqslant \overline{x_t} \quad (4)$$

where the decision variable x_t represents the flow of water used for power generation on day t; the function $\Pi_t(x_t)$ represents the daily financial revenue at the moment t, which (see below for details) is assumed to increase at a decreasing rate with the amount of water used to produce energy. The upper case E underlines the fact that companies' decisions are based on imperfect information concerning the future values of critical variables, such as the level of the reservoir and future energy prices (i.e., nature and market uncertainty imply that the objective function is in fact the expected value of the energy produced; thus, the model avoids the problem of most optimisation models that assume that companies have "perfect hydrological foresight", which leads to unrealistic results). The state variable z_t measures the amount of water stored in the reservoir on day t; its dynamics are represented by the transition function (2), where the state of the system on the following day depends, first, on its state the previous day, second, on the exogenous net inflow of water (y_t) obtained from the river basin net of the evaporation and the abstractions taken from the reservoir for other uses that are out of the control of the hydropower operator and, finally, on the decision made by the hydropower operator on day t, x_t.

Constraint (3) shows the boundaries of the state variable z_t on any day. The left term of this constraint shows the minimum level of water stored ($\underline{z_t} \leqslant z_t$). This lower bound is the value determined by the technical requirements of the infrastructure or by the institutional requirement to guarantee a minimum water availability for other present and future uses. Thus, the lower limit may vary in different seasons or months (depending, for example, on seasonal crops requirements). The right term of the constraint (3) shows the upper bound of the amount of water stored ($z_t \leqslant \overline{z_t}$), which also may depend on different factors, such as the reservoir's storage capacity or the flood limit to avoid the flooding of downstream riverine villages (which may also vary during the year according to flood risk perceptions).

Constraint (4) shows the boundaries of the daily decision variable, x_t. The lower bound ($\underline{x_t} \leqslant x_t$) may come either from a minimum environmental flow, from the requirement to deliver given amounts of water to other water uses downstream or, alternatively, from any water authority requirement to release a certain amount of water at the date t (for example, for an artificial flood). In a similar way, the relevant upper limit ($x_t \leqslant \overline{x_t}$) is the higher value among the quantity of water resulting from the hydropower generation plant maximum capacity. Provided that the plant is not always functioning at its full capacity, none of the above-mentioned constraints is binding, and the operator is able to distribute the energy produced among the different days of the year in order to maximise its revenue[3].

Decision (2) consists of choosing the hourly production of electricity in a particular day. This decision can be represented by the following daily revenue maximisation problem:

$$\max_{x_t} \Pi_t = \sum_{k=1} p_{tk} \alpha x_{tk} \quad (5)$$

$$\underline{x_k} \leqslant x_k \leqslant \overline{x_k} \quad (6)$$

$$\sum_{k=1}^{24} x_{tk} = x_t. \quad (7)$$

The objective function in this case, π_t, represents the daily financial revenue. This revenue depends on the following: (i) the decision variable (x_{tk}),the quantity of water used for power generation per hour (k), (ii) the corresponding prices, (p_{tk}), which are assumed to vary in a predictable way (t) depending on the season, the day of the week, weather conditions and other factors that are known in advance by the operator, and (iii) an input–output technical parameter (α) measuring the volume required to produce one unit of electricity. Under these conditions, the operator finds the optimal distribution of the energy produced during the day (producing at a maximum capacity at peak price and minimising the energy delivered to the market when electricity demand is at its lowest). The variable and fixed costs of producing hydroelectricity can be considered negligible; accordingly, variations in the revenue function reflect changes in financial returns. The decision variable (x_{tk}) is subject to the same upper and lower bounds as in the first problem, but the relevant time units are now hours instead of days (as in (6)).

Provided that there is detailed data on both the hourly market price of electricity and all of the relevant constraints on the decision variable x, obtaining a closed solution for decision problem (2) becomes straightforward. The solution of this problem for the range of all of the likely values of the daily decision x_t is the financial revenue function $\pi_t = F(x_t)$. This maximum daily revenue function is concave and non-decreasing and varies on different days during the year according to random and seasonal changes in electricity demand and supply.

Problems (1) and (2) are closely linked. On the one hand, the overall quantity of water delivered in the solution of problem (2) must equal the optimal decision of the first problem for the corresponding day (as in constraint (7)). On the other hand and most importantly, the optimal solution of problem (2) is nested in the definition of problem (1). In other words, the maximum revenue as a function of the decision variable (x_t) becomes the main argument, and its expected value in the future is the objective function of problem (1). Thus, when deciding how much water to use each

[3] In fact, the key role played by hydropower in the stabilization of the electricity supply system implies the presence of spare capacity ready to be used to turbine water at peak demand hours. In the last 10 years, hydroelectricity in Spain used less than 20% of its installed power production capital (Gómez, 2009).

day, the operator knows how this water can be delivered at any time to obtain the maximum revenue in the electricity market.

3.2. The model calibration

The maximum daily revenue function above is an important step in the calibration of daily production decisions as represented in problem (1). Nevertheless, finding the analytical solution to problem (1) is not an easy task given its dynamic nature, the wide time span that needs to be considered and the uncertainty associated with natural water inflows and energy markets. A theoretical solution requires assuming either perfect hydrological foresight or accepting strong assumptions about the operator's risk attitude. Instead of finding the analytical solution of problem (1), we have the option of deducing its solution from the decisions that the operator has taken in the past under a given set of conditions.

Therefore, we use detailed data on the decisions taken by the operator in the past (on different days, under different decision constraints, and in different states of the river system) to obtain econometrically the operator's underlying decision function of using water and producing energy. This function (problem (1)) and the maximum daily revenue function (problem (2)) provide the representation of the optimal behaviour of the operator in the baseline scenario. These two functions and the information set of observed decisions and constraints are all that we need to represent the operator's behaviour and assess the opportunity cost of imposing the delivery of a flushing flow.

The information used in this paper comes first from the daily data on the level of water stored in the three reservoirs and their hourly outflow of water provided by the Hydrological Information Automatic System (SAIH) of the Ebro River Basin Authority (ERBA, 2012a). We use data from September 1997 to October 2008. This 11-year period encompasses several hydrological cycles during which regulations over water use have been relatively stable, as defined in the River Basin Management Plan (ERBA, 2012b). Secondly, the River Basin Authority has also provided an entire set of data on the relevant constraints with which the operator must comply. These data include the following: the minimum flows, set at 100 $m^3 s^{-1}$; the amount of water that was required to be supplied by the reservoir system for other uses different from power generation in any given month; and the monthly changing minimum level of water stored in the MRFDC determined by the water authorities to guarantee water supply at any time. Finally, the hourly price of electricity was obtained from the Spanish Electricity Market Operator (SEMO, 2013), and the quantity of electricity produced by the hydropower operator at any moment was deduced from the outflow of water and the technical characteristics of the power plants in each reservoir (we assume a standard 0.8 energy conversion efficiency). In this way, we have observations for all the parameters and for all the state and decision variables implied in the optimisation problems (1) and (2) for a total sequence of 4017 days. This sample provides both the data required for calibrating the base model and the scenario to assess the opportunity cost of the flushing flow programme.

The *first stage* in calibrating the model deals with optimisation problem (2). The daily financial returns are a maximum argument function of the following: the amount of water used for power generation, the set of hourly prices of the day, the minimum flow set by water authorities and the maximum production capacity of the plant. Fig. 3 shows the daily financial return function obtained from using hourly prices and the production capacity and the minimum flows for three selected months: (i) December, when water demand and the average price are that their highest, (ii) March, when prices are the lowest, and (iii) January, when the price is close to the yearly average. As can be observed, the financial return function increases at a decreasing rate with the volume of water.

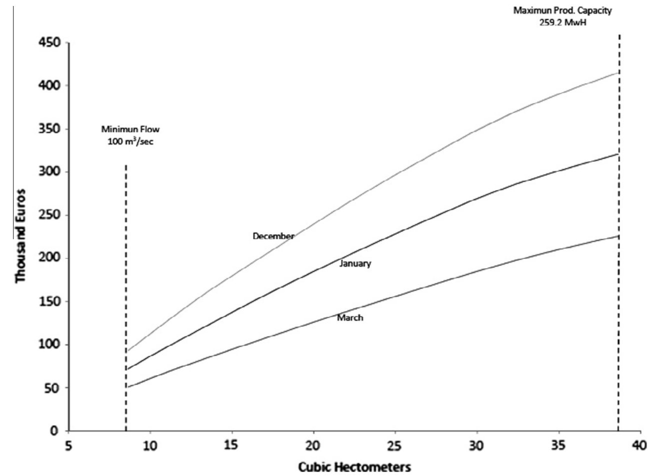

Fig. 3. The optimal daily revenue function in the upstream Mequinenza Power Plant. *Source*: Own elaboration.

Once the minimum flow is satisfied, the decreasing marginal productivity of the water input is caused by the fact that at lower production levels, the energy is produced at peak price time; any increase in water use implies selling the energy at a decreasing price. Daily income is also bounded by the maximum capacity of the plant.

Once the optimal financial returns are determined, this information is introduced in the intertemporal decision problem (1) to obtain the optimal decision profile of how much water to use any day, considering the transition equation (2) and the technical and policy constraints of the baseline scenario. The ability of the operator to obtain rents from market price variations is one of the key elements that are affected by the requirement to adjust water delivery to a pre-designed flushing flow scenario.

The *second stage* of model calibration deals with optimisation problem (1), which is associated with the decision on the daily outflow of water. Obtaining an explicit functional form of the optimal daily decision profile x_t is not feasible given the number of parameters involved and the stochastic nature of the problem. Nevertheless, the number and the details of the available data in the sample allow for an empirical approximation of this optimal value function with econometric techniques; this circumstance allows revealing the functional form that better explains the observed behaviour of the operator. We thus expect the decision variable (x_t) to be an increasing function of the amount of water stored (represented by the state variable z_t) and the water inflow received from the basin on the previous days, y_t. As this relationship is not linear, we use a maximum likelihood estimation method to obtain the better fitting function among the Box Cox power transformation family of functions. In addition, as restrictions over the minimum level of the stored water and the other uses of water that are different from electricity production vary from month to month, we also used dummy variables for every month of the year. The empirical model is then as follows:

$$x_t(\mu) = \alpha_1 z_t(\lambda) + \alpha_2 y_t(\eta) + \beta_i, \tag{8}$$

where λ, μ and η are the Box Cox transformation parameters:

$$x(\mu) = \frac{x^{\mu} - 1}{\mu} \cdot z(\lambda) = \frac{z^{\lambda} - 1}{\lambda} \cdot y(\eta) = \frac{y^{\eta} - 1}{\eta} \tag{9}$$

and the coefficients $\beta_i (i = 1, \ldots, 12)$ represent the fixed effect parameters for any month that is included in the model as dummy variables. The variable y_T measures the overall net inflow from the

Table 2
Box Cox estimation of the daily outflow of water. *Source*: Own elaboration.

Variable	Coefficient	Standard error	Significance (%)
Water stored (h m^3)[a]	0.0009339	0.0368078	99
Lag water stored (h m^3)	0.1480627	0.00718118	99
Water inflow (h m^3/day)	0.48437	8.13874E−05	99
October	−12.4484	1.34145119	99
November	−11.278	1.34805527	99
December	−10.647	1.3814159	99
January	−8.71131	1.39861698	99
February	−9.53085	1.40190417	99
March	−8.7341	1.41103021	99
April	−10.3591	1.44114208	99
May	−10.9435	1.47712765	99
June	−13.4476	1.48860571	99
July	−12.3389	1.44571131	99
August	−12.4329	1.37090634	99
September	−12.8491	1.32810979	99
λ	0.383011	0.00718118	99
Wald test	34.07		
Elasticity of water stored	1.14593		
Elasticity of water inflow	0.79495		
Elasticity of lag water inflow	0.35503		

[a] Variables transformed by λ.

upstream river basin and helps to include variations explained by dry or wet years.

This function of the private decision on how much water to deliver on any day, along with the maximum revenue function determining how to distribute this water during the day to produce energy, allows the calibration of the model for the complete sequence of all of the days in the sample. Table 2 shows the econometric results. Transformation parameters μ and η were not found to be significantly different from 1; therefore, the associated variables x_t and z_t enter linearly in the equation. The maximum likelihood value of the nonlinear transformation parameter (λ) was determined at 0.35. All of the remaining coefficients are significant at a 1% level. Apart from maximum likelihood criteria, the final equation fulfils Wald's and Lagrange's multiplier tests for the optimisation of the econometric estimation. The size and detail of the sample seem to be important factors behind the robust and efficient econometric estimation of the daily decision variable.

This baseline scenario and the associated optimisation functions are the basis by which to assess the impact of flushing flows over the quantity and value of the energy produced.

4. Results

Flushing flows are implemented through the imposition of particular constraints over the operating rules of the hydropower plant. These constraints imply a deviation from the profit maximising decision profile (baseline scenario) with a negative impact on expected financial profits. The revenue variation, or the opportunity cost, is moreover the net result of two different effects of opposite sign. The first effect is the immediate revenue increase, as controlled floods require the delivery of an amount of water that exceeds the quantity that the operator would have chosen otherwise. The second effect is the decreased revenue resulting from the reduction in the stock of water available after the flood[4] during the days or weeks required for the reservoir to come back to its baseline level. Once this convergence is complete, not only will the amount of water stored be back to normal but the operator's decisions and revenues will also be the same as in the baseline scenario. The absorption period, or the time during which water stocks, flows and profits diverge from the baseline, is a measure of the time required by the system to absorb the shock produced by the flood[5].

The cost of the flushing flow can be reduced by a careful selection of the right moment at which to start delivering the water for the subsequent hours. Although the operator cannot decide upon the day and the quantity of water to deliver during the artificial flood, it can choose the right hour at which to start the flood. This decision allows minimising foregone revenues, as expected energy prices vary in a predictable way during the day. Fig. 4 shows the market value of the energy obtained during the flood for the autumn and spring seasons according to the flushing flow hydrograph shown in Fig. 2.

The correct selection of the time to start delivering the water might explain differences as high as 40% of the maximum revenue, or an opportunity cost of as much as EUR 160,000 per flood. In what follows, we assume that the delivery of water always starts at a time that maximises the value of the energy produced during the flushing flow (thus minimising the opportunity cost of the flushing flow).

Provided that the artificial flood is feasible (which occurs when water level is above a minimum critical level) and its starting point has been chosen to minimise its impact over the value of the electricity produced, we are now ready to analyse the opportunity cost of flushing flows. Fig. 5 presents the overall opportunity cost for the days in the sample when the flood is feasible in autumn (Fig. 5a) and spring (Fig. 5b). The revenue variation is measured on the left axis. The figure is complemented with data about the amount of water stored in the upstream reservoir on the day of the flood, which is measured on the right axis.

As expected, the opportunity cost of flushing flows changes with the condition of the system. The profit maximising opportunity cost varies from EUR 33,000 (revenue variation: −33,000) to EUR 76,000 (−76,000) for the spring and autumn floods, respectively, for a total opportunity cost of 109,000 EUR per year (−109,000). The standard deviation of the opportunity cost equals 55,000 for the spring flood and 110,000 for the autumn flood, denoting a high variability that is largely the result of the irregular water flows observed in the case study area. In the same way, the absorption time varies from a few days to several months with an average value of 82 days and a standard deviation of 50[6].

5. Discussion and conclusions

Flushing flows have been shown to be effective means to achieve successful river restoration (Hueftle and Stevens, 2002;

[4] Under extreme events, the implementation of flushing flows may lead to additional opportunity costs. For example, when the amount of water stored in the reservoirs is below or at its lowest or minimum acceptable level, flushing flows would imply a reduction of the water supplied for crops or any other uses. In any case, despite being technically feasible, the River Basin Authority clearly establishes a series of priorities under extreme events that rule out the possibility of implementing flushing flows (ERBA, 2007).

[5] The flushing flows alter the decision making process of the hydropower operator, moving away the observed stocks and released water flows from the optimal path (baseline). As a response to the lower water stock in the dam resulting from flushing flows, the hydropower operator will release less water than he would otherwise do in the baseline scenario without flushing flows. This will happen until the amount of water stored in this alternative scenario finally converges to the amount of water stored in the baseline scenario. This time span is known as the absorption period.

[6] Operator's decisions in our model are based on expectations over the water inflow that the reservoir might receive in the future. These expectations might or might not be fulfilled, and the consequence of this circumstance is that the opportunity cost may actually differ from its expected value (depending on rainfall on the days following the flood) and can even be negative. Given the timing of the different effects and, particularly, the fact that the increase in revenue occurs at the start of the flood, while the cost is different along the absorption time, the succession of wet days can shorten the absorption time, and when the reservoir recovers rapidly enough, it can even avoid a negative opportunity cost. This outcome is observed on the days when the revenue variation of the flood is positive (see Fig. 5).

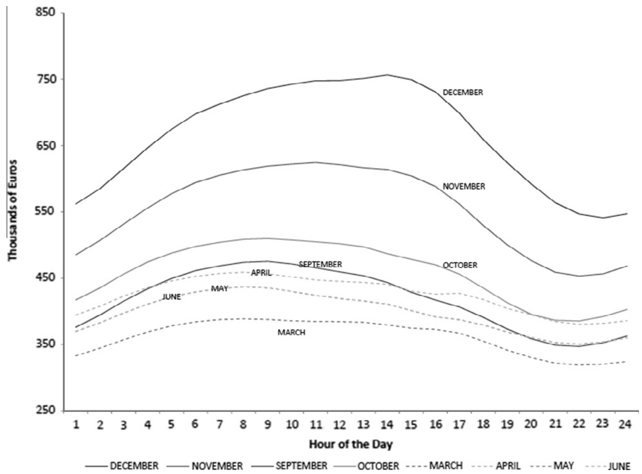

Fig. 4. The optimal timing of the flushing flow in the Lower Ebro River. *Source*: Own elaboration.

Vinson, 2001; Kondolf and Wilcock, 1996). While the benefits and technical effectiveness of this alternative are widely known, the tradeoffs in terms of the economic uses of water are often considered too high and prevent the periodical release of artificial floods. In this paper, we present a planning-level methodology for the assessment of such opportunity costs in heavily modified downstream areas where flushing flows affect the operational rules of hydropower facilities. We show how the model can be calibrated with a combination of a deterministic maximum revenue function for the hourly delivery of water and an econometrically obtained decision function for the daily amount of water delivered. The model enables us to analyse the impact of imposing a new operation rule on the hydropower operator's optimal decisions. This rule requires the release of water during certain periods of time in accordance with an artificial flood regime purposely designed to restore the basic functions of a river ecosystem. As the technical design, feasibility and opportunity cost of flushing flows heavily depend on the intrinsic conditions of river ecosystems, we used the detailed time information about the stocks and flows of water in the Lower Ebro River to calibrate and simulate the model for all of the days in spring and autumn in the sample when an artificial flood is feasible.

Implementing flushing flows on a regular basis will result in a reduction in the asset value of affected hydropower facilities, as they will have to operate under more stringent institutional rules. The case study shows that hydropower facilities in the Lower Ebro can provide the artificial flows required for the restoration of the river channel at a cost that is equivalent to a small fraction of the energy delivered to the market and the overall annual revenue. The expected opportunity cost of two floods per year (EUR 109,000) is equivalent to 0.17% of the average yearly revenue and is only a fraction of the average daily revenue (which amounts to EUR 250,000 in the sample days).

The cost of guaranteeing the periodical release of flushing floods by changing the operation rules of hydropower facilities also seems to be lower than any other alternative of obtaining water from other sources (such as saving water in agriculture and domestic consumption or water recycling and desalination) to have additional stored water available for this purpose in the reservoirs. Each artificial flood requires the delivery of approximately 36 million cubic metres over sixteen hours; considering the opportunity cost estimated at EUR 76,000 and EUR 33,000 for the autumn and the spring floods, respectively, we can conclude that the cost per cubic metre delivered is lower than EUR 0.002 for the autumn flood and less than half of that quantity for the spring flood. Experience shows that there are few alternatives to obtaining such a large amount of water at a lower cost from other economic uses.

Provided that flushing flows are implemented with sound economic criteria, their opportunity cost is small when compared to people's Willingness To Pay (WTP) to secure the benefits of river restoration programmes. Original estimations in areas that resemble our policy context show that WTP ranges from EUR 5.3 to EUR 63.6 per person per year (Loomis et al., 2000; Meyerhoff and Dehnhardt, 2007; Berrens et al., 1998; Brown and Duffield, 1995; Colby, 1993; González-Cabán and Loomis, 1997). Depending on the size of the population benefited by the programme, the opportunity cost of flushing flows can range from EUR 0.55 (if we consider the 200,000 people living in the Lower Ebro River) to EUR 0.04 per person per year (if we consider the 2.8 million people living in the entire Ebro Basin) (ERBA, 2012b).

However, these values should be taken with caution. The WTP for the benefits associated with river restoration programmes may be actually lower as a result of the distance decay problems typically associated with environmental quality valuation (Hanley et al., 2003; Bateman et al., 2006). Also, the opportunity cost of flushing flows of 109,000 EUR per year should not be regarded strictly as a lower bound; rather, it is a reference value sensitive to uncertainty. Actually, the uneven behaviour of flows and stocks of water in Mediterranean rivers (ERBA, 2012a) and the volatility of energy prices (SEMO, 2013) make operator's revenue highly variable. Assuming that hydropower operators are risk averse, they would be willing to accept a lower compensation for the losses derived from a flushing flow, as long as this value is secure (*certainty equivalent*). The difference between this compensation and the opportunity cost of flushing flows is a function of the operator's risk aversion coefficient, which varies for every area and type of agent (e.g., risk aversion is higher in drought prone areas such as the Guadalquivir River Basin than in more resilient basins, see Gutiérrez-Martín and Gómez, 2011). Although revealing the risk attitude of hydropower operators is beyond the scope of this paper, these considerations need to be addressed in future research and bargaining processes.

In spite of this, our results show that the opportunity cost of flushing flows is expected to be between 9.74 and over 1633 times lower than the benefits associated with the river restoration programmes, as measured by individual's WTP. These figures suggest that the real policy challenge consists in finding the institutional agreement to implement the flushing flood programme and agreeing on the potential compensations[7] to overcome the incentive problem. The considerable mismatch between the opportunity cost and the societal benefits provides sufficient room for private operators and public authorities to conduct successful bargaining and thus agree on the voluntarily compliance of a soundly designed programme of flood releases to restore the critical functions of the water ecosystem. The cooperation between power generation companies and water authorities is also a positive signal, showing that flushing flows for river restoration purposes can be compatible with private corporate interests. These efforts are now considered to be the pioneering phase of a comprehensive restoration programme of the whole river's ecosystem and a key piece of the River Basin

[7] The MRFDC was built by the hydropower operator in exchange of a long term government concession to exploit the dam complex. The contract did not include the possibility of implementing flushing flows (i.e., larger temporary outflows), nor a reduction in the water inflows. In the past, the modification of this contract (e.g., through increased water rights upstream that reduced water availability for hydropower generation) has been solved with compensations to the operator, sometimes in the form of larger concession periods (e.g., GRC, 1997). Accordingly, in the current context making the hydropower operator pay for the flushing flows cost is unlikely and would require a modification of the legal framework.

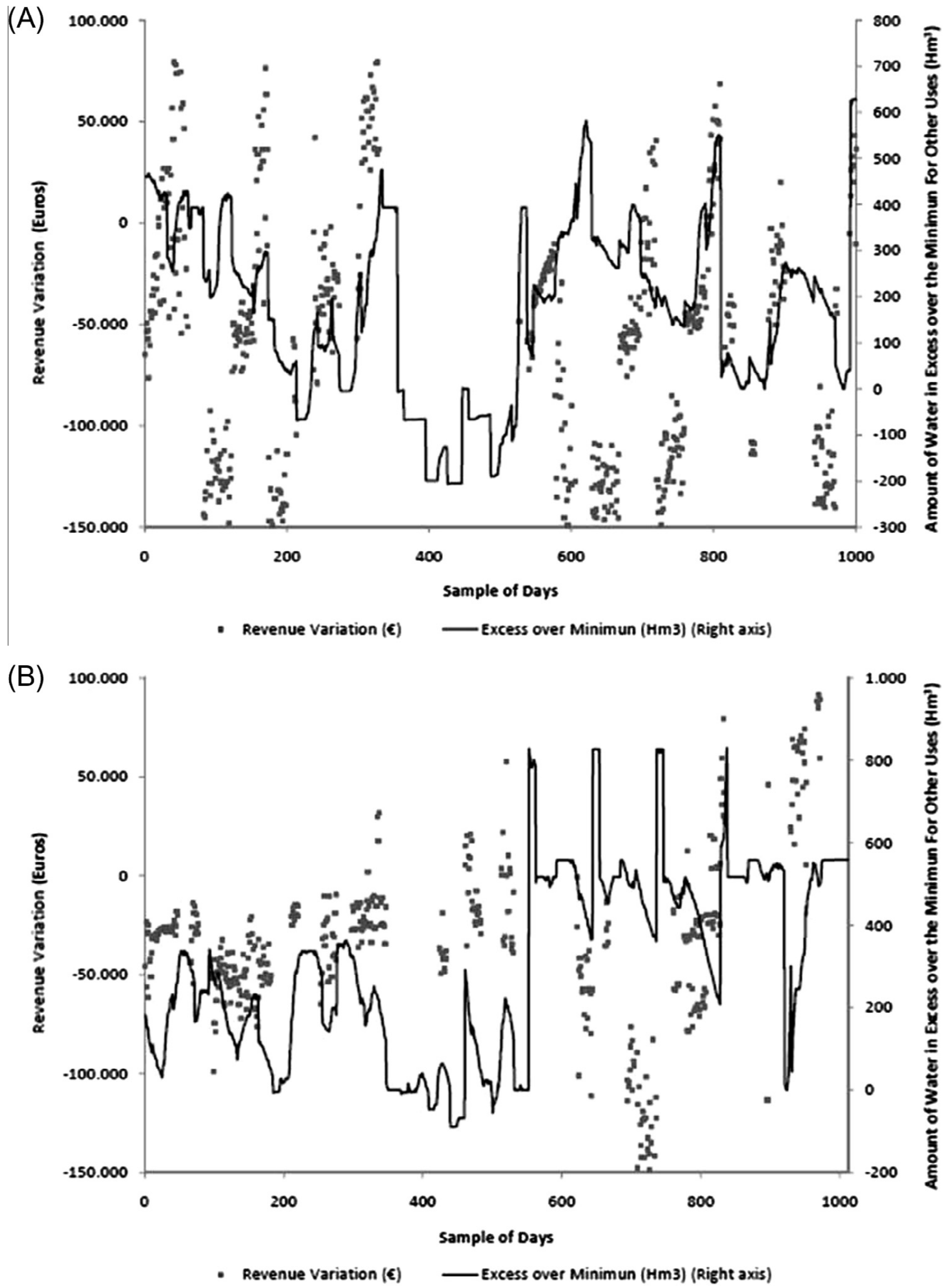

Fig. 5. The opportunity cost of a flushing flood in the Lower Ebro. (A) Autumn. (B) Spring. The sample of days includes the sequence of autumn (A) and spring days (B) in the total sequence of 4017 days (ERBA, 2012a). *Source*: Own elaboration.

Management Plan that is being elaborated for the implementation of the WFD.

Also, this research on the opportunity costs of flushing flows may offer useful insights for basins that resemble our case study area. There is still little research on the costs of reallocating water from economic uses to the environment, with the exception of some studies on the tradeoff between agriculture and environmental flows (Sisto, 2009; Troung, 2012; Pang et al., 2013). However, as shown above, the implementation of flushing flows in heavily engineered rivers like the Lower Ebro River may be more cost-effective if the necessary water is taken from alternative uses with a lower opportunity cost than agriculture (i.e., hydropower), provided that other uses are not affected. Moreover, the large amounts of water required and the short time span during which flushing flows are released may make hydropower the only feasible alternative. This paper aims to provide a standard method to estimate the tradeoff between flushing flows and hydropower generation. This methodology may be transferred to other heavily engineered rivers in which hydropower facilities can be used to reproduce the functions previously performed by the natural system and thus to achieve a better ecological status. This is the case of many rivers in semi-arid areas, which tend to be more heavily impounded and thus their hydrology more strongly affected than rivers in humid climates because demand for water is greater and runoff is out-of-phase with demand. For example, in the Sacramento and San Joaquin Rivers of California (US) the impounded runoff index (ratio of reservoir capacity divided by mean annual runoff) is 0.8 and 1.2, respectively, and the flood peaks have declined on average

53% and 81%, respectively. Therefore, flushing flows have the potential to achieve a better environmental status (Kondolf and Batalla, 2005). In these rivers runoff is lower than in the Lower Ebro River, pressures are more intense and the hydrograph is flatter (the decline of the flood peaks is estimated at 30% in the Ebro River) (ERBA, 2012a; Kondolf and Batalla, 2005), all this suggesting larger opportunity costs and absorption periods for flushing flows than in our case study area (but also potentially larger environmental benefits), though all this should be confirmed with on-site estimations. Similar results could be expected with the flushing flows proposed by Wu and Chou (2004) in the Trinity River in northern California. The estimation of the opportunity costs of flushing flows is also of relevance in the lower stretches of the Colorado River (US-Mexico border), where the recently approved Minute 319 created a pilot programme that required water users in the U.S. and Mexico to provide a one-time high-volume flushing flow (or *pulse* flow) of 129.5 million cubic metres (IBWC, 2012). However, since water scarcity is much more acute in this area (the delta of the Colorado River has run dry during most of the last half century) (Glenn et al., 2008; Wheeler et al., 2007; ERBA, 2012a), opportunity costs are likely to affect other uses apart from hydropower generation and therefore a more extensive assessment framework involving other economic activities would be required in this case. Flushing flows have also been implemented to prevent algal blooms downstream the Opuha Dam in New Zealand (Lessard et al., 2013), though with limited results as a consequence of the inability of the dam to generate floods similar to pre-dam levels. This area resembles our case study, with hydropower being the most affected economic activity. In this and similar cases, the estimation of the opportunity costs is of especial relevance in order to justify (or not) the implementation of flushing flows from a cost-benefit perspective.

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