APPLYING THE POLLUTER PAYS PRINCIPLE TO QUANTIFY THE ENVIRONMENTAL COSTS CAUSED BY LARGE-DAM FLOW REGULATION

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Summary

Availability of water for irrigation, hydroelectric production and domestic or industrial supply usually require dams and reservoirs, which severely affect river ecosystems. Although the Water Framework Directive states that activities causing environmental damage are financially responsible, environmental costs associated to river damming are not being properly internalized in the current procedures of water pricing until now.

We propose a methodology to evaluate the environmental costs of flow regulation based on the "polluter pays" principle, where the amount to be paid is proportional to the intensity, duration and frequency of the resulting hydrological change. This is a dynamic water pricing approach which is determined by the hydrologic alteration that the river suffers at every time instant (changes in river flow due to flow regulation). The procedure includes three steps: (i) assessing the admissible range of regulated flow variability, (ii) estimating the daily environmental impact of regulated flows, and (iii) calculating the environmental costs of flow regulation. This paper applies the proposed methodology in rivers regulated by large dams from North of Spain (Duero and Ebro Basins) and Central (Tajo Basin) and quantifies environmental costs for the flow regulation caused by 32 different dams. The advantages over other water cost valuation methodologies are discussed.

The methodology was used to develop an R package called *'FlowRegEnvCost: The Environmental Costs of Flow Regulation'* that is available online. The approach enlarges the current recognition of water environmental costs and represents a practical management tool for achieving the objectives of the WFD. It advocates for decreasing environmental impacts of flow regulation and increasing efficiency in water use as allows a clear visualization of the potential impacts and costs of the flow regulation, thus facilitating communication and discussion among environmental actors. Also, it can optimize (balance between sustainability and efficiency) the most appropriate time of the year for water releases from the dam, thus, minimizing the environmental cost and maintaining the profitability of the use. Therefore, this study may achieve

sustainable water management functioning as a mechanism of self-control to avoid further degradation when regulating flows.

Keywords: Flow regulation, Environmental costs, Dam, Water, Water Framework Directive

1. INTRODUCTION

Economic analyses are gaining a key role in water policy, providing valuable information for developing sustainable management of water bodies. The Environmental Liability Directive (2004) establishes a framework to prevent and remedy environmental damages based on the polluter pays principle. However, the European Water Framework Directive (WFD) is more explicit requiring economic analysis of water uses for both purposes (i) assessing the level of recovery of costs of water services and (ii) estimating the potential costs of restoration measures.

Environmental costs of flow regulation have been very poorly developed in comparison with pollution or other impact-pressures. Although many attempts have been made in formulating methods and applications of economic principles to achieve the environmental objectives of the WFD (WATECO, 2003; Babulo et al., 2011; Bithas et al., 2014), water users still do not pay the full cost recovery of water supply. Environmental costs are usually the first ones which are not fully recovered, partially due to the complexity of nonmarket valuation.

Flow regulation by dams and reservoirs is considered as one of the most frequent source of environmental impacts in rivers (Nilsson et al., 2005; Poff et al., 2007) and one of the most important threat for river biodiversity at global scale (Vörösmarty et al., 2010). Despite there being a multitude of approaches assessing environmental costs based on people’s preference and production function (e.g. Hanley and Barbier, 2009) there is a lack of approaches assessing environmental costs proportionally to the impact produced by flow regulation. Our study aims to offer a new approach for assessing the environmental costs of flow regulation based on the intensity of the hydrological alteration of the natural flow regime. We propose a dynamic water pricing approach which is determined by the hydrologic alteration that the river suffers at every time instant (i.e. changes in river flow due to flow regulation).

In previous work we have developed a new approach (García de Jalón et al., 2017a) to assess and estimate the environmental costs of flow regulation based on the polluter-pays principle. This approach is based on the analysis of daily flow data that may be implemented using ‘R’ software (Package FlowRegEnvCost, García de Jalón et al., 2017b). The objective of this paper is to apply this approach to quantify Environmental Costs of Flow Regulation by dams based on ‘regulator-pays principle’ caused by the resulting flow regulation by Spanish Large Reservoirs.

2. STUDY SITES

The proposed methodology has been applied in 32 large dams located in three Spanish different river basins: Duero Basin (12 dams); Ebro Basin (12 dams) and Tajo Basin (8 dams). In figure 1 location of these dams and their reservoirs are shown.

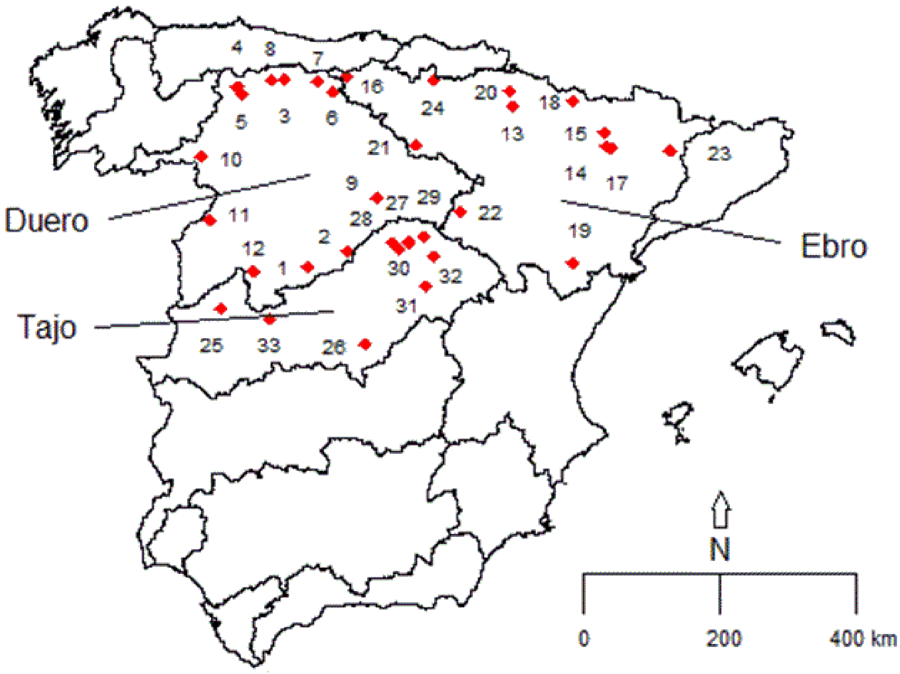

Figure 1. Location of the 32 large dams in which Environmental Costs from hydrological impact is assessed.

3. METHODOLOGY

The methodological approach developed quantifies water prices including environmental costs taking into account that flow regulation costs are proportional to the hydrological alteration and its ecological impact. It can be applied to any regulated river reach in which pre-dam and post-dam flow data are available.

The methodology can be separated in three steps:

a) Admissible range of flow variability: the first step is based on the natural flow regime, studying the hydrologic conditions before the river is regulated the range of admissible flow variability. Reference admissible (i.e. acceptable values) area of flow variability as the range of values between the 10- and 90- percentiles of each daily flow within the years in which the river flow was not regulated.

b) Estimation of flow regulation impacts: Second step evaluates the environmental impact due to flow regulation of each river reach at any time instant by assessing the hydrologic alteration (when the circulating flow is outside of the admissible range) according to deviance from natural flow regime. Two types of impacts are considered High-flow (environmental impacts due to discharges greater than the upper limit of the admissible range) and Low-flow impacts (impacts due to discharges lower than the lower limit of the admissible range). Both impacts are calculated as the distance greater from the high (90 percentile) and the distance low (10 percentile) limits of admissible area of discharges. Figure 2 shows an example in Riaño Dam (R. Esla) of how the High-flow and Low-flow impacts are exhibited. It is noteworthy to highlight that a flow peak in June which is by far higher than in any day in July and August does not generate an extreme High-flow impact. This is explained by the fact that the duration of the impact is rather short.

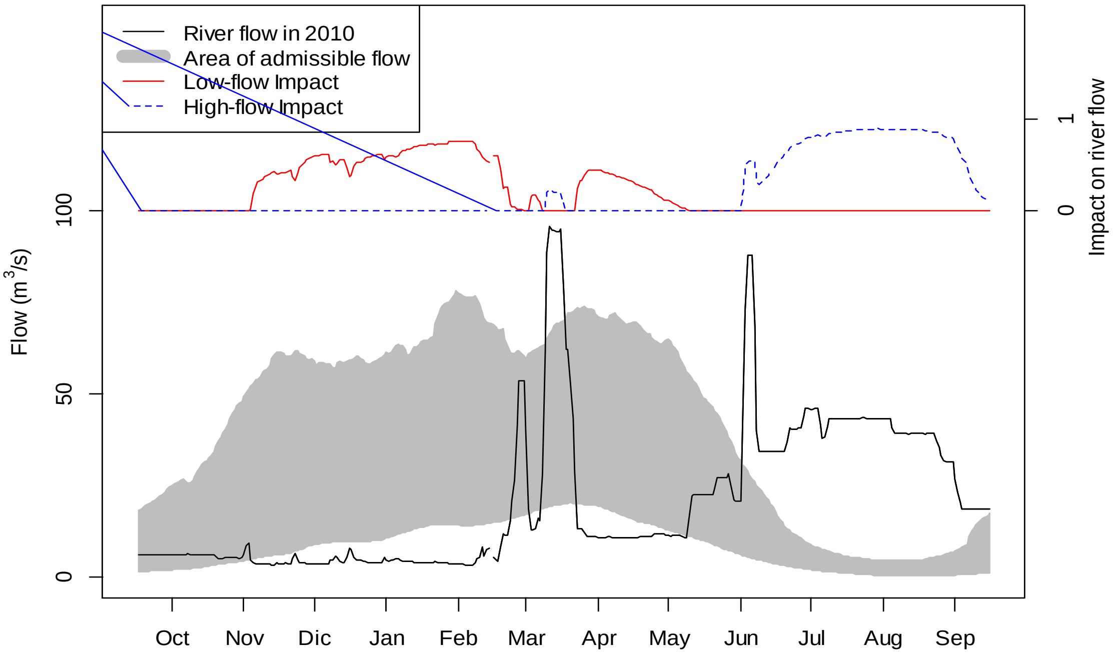

Figure 2. Example of Low-flow and High-flow impacts during 2010 in Esla River (Riaño, Spain) calculated as the distance from the admissible area of discharges.

c) Environmental Costs of flow regulation Assessment: the last step is to estimate environmental costs of regulated flow Impacts which are calculated as a function of the environmental impact of flow regulation. Thus the environmental cost in a time instant *t* (i.e. day) is calculated as the product of the environmental impact of flow regulation in the previous time instant (i.e. the day before) and the function Ku which is measured in euros per cubic meter of regulated water:

$$Regulation\ costs_{i,t}\left(\frac{€}{m^3}\right) = Impact_{i,t} * Ku_{i,t}\left(\frac{€}{m3}\right) \qquad Eq.1$$

where function Ku depends on the regulation Impact, that increases exponentially with the impact:

$$Ku_{i,t}\left(\frac{€}{m^3}\right) = a_{i,t}\left(\frac{€}{m^3}\right) * \exp^{b_{i,t} * Impact_{i,t}} \qquad Eq.2$$

Where $a_{i,t}$ is a coefficient measured in € per cubic meter and represents the price of water. Society must decide on its value base on daily costs of water regulation rights, or by daily fees and taxes of public water concessions, etc. $b_{i,t}$ is a coefficient that captures the vulnerability or conservation interest of the regulated river reach.

For this paper, and in order to compare differences among basins, rivers, dams and regulation impacts, environmental costs of flow regulation have been calculated for the same period (2001–2010) and assigning the same values to the parameters: a = 0,001 (€/m^3); b =2.

Once the regulation costs in € per cubic meter is calculate (Eq. 1), mean daily costs can be calculated following Equation 3:

$$Mean\ daily\ cost\left(\frac{€}{d}\right) = Regulation\ cost\left(\frac{€}{m^3}\right) * \bar{Q}\left(\frac{m^3}{s}\right) * \left(\frac{86{,}400\ s}{1\ d}\right) * RI\ (unitless) * PWR\ (\%) \qquad Eq. 3$$

Where $\bar{Q}$ is the mean river flow converted measured in cubic meter per day. RI is the regulation index measured as the ratio between the reservoir volume in cubic hectometres and the annual water contribution to the reservoir in cubic hectometres. PWR is the proportion of water regulated in the river reach. As data on the proportion of water regulated in each river reach was not available, in this study we assumed a 25% value.

4. RESULTS

4.1. Flow Regulation Costs

Following the proposed methodology, we first calculated the admissible range of flow variability in each river reach based on the daily flow data during the pre-dam period. Subsequently, High- and Low-flow impacts were calculated as a function of the difference between the circulating river flow and the admissible range of flow variability (see García de Jalón et al. (2018) for more details in the calculation in the studied rivers). The last step calculated the environmental cost due to flow regulation following equations 1, 2 and 3. The environmental costs of flow regulation in 2010 in the studied rivers are shown in Table 1.

Regulation costs within the Duero Basin ranged from 0.05 €/m3 in Pontón Alto dam to 0.98 €/m3 in Cernadilla. Within the Ebro basin, they ranged from 0.005 €/m3 in Mediano to 1.12 €/m3 in Reinosa. Within the Tajo basin, they ranged from 0.12 €/m3 in Tejera to 1.47 €/m3 in Gabriel y Galán.

Mean daily regulation costs within the Duero Basin ranged from 200 €/d in Pontón Alto to 252,000 €/d in La Almendra. Within the Ebro basin, they ranged from 100 €/d in Monteagudo to 253,000 €/d in Reinosa. Within the Tajo basin, they ranged from 1,000 €/d in Atance to 885,000 €/d in Gabriel y Galán.

Table 1.- Mean Environmental Costs from flow regulation (yellow) for each dam studied for the period 2001-2010. Second and third rows correspond to mean annual flows and regulation indices for each

reservoir. The fourth row corresponds to average daily Costs taking into account values of previous rows.

Reservoirs:	Aguilar de Campoo	Almendra	Barrios de Luna	Cernadilla	La Magdalena (Selga)	Las Cogotas	Linares del Arroyo	Ponton Alto	Requejada	Riaño	Santa Teresa	Vegamian
Regulation cost (€/m3)	0.23	0.29	0.79	0.98	0.38	0.49	0.53	0.05	0.39	0.53	0.33	0.31
Mean annual flow (m3/s)	9.70	40.90	13.80	13.90	13.80	2.80	2.40	2.90	5.10	18.90	25.50	9.90
Regulation ind.	0.81	2.05	0.71	0.58	0.10	0.67	0.73	0.08	0.41	1.08	0.62	1.02
Mean daily cost (1000€/day)	39.59	252.10	166.16	170.61	11.40	20.03	20.24	0.23	17.41	216.76	111.19	66.39
Reservoir:	**Barasona**	**Bubal**	**El Grado I**	**Itoiz**	**Mansilla**	**Mediano**	**Monteagudo**	**Oliana**	**Reinosa**	**Santolea**	**Ullivarri**	**Yesa**
Regulation cost (€/m3)	0.30	0.02	0.03	0.16	0.46	0.00	0.10	0.25	1.12	0.05	0.05	0.21
Mean annual flow (m3/s)	23.60	12.30	42.20	15.30	5.60	40.60	0.05	29.70	10.40	3.30	6.20	42.90
Regulation ind.	0.11	0.16	0.30	0.86	0.39	0.34	3.17	0.09	1.65	0.46	0.75	0.33
Mean daily cost (1000€/day)	16.80	0.96	7.73	44.65	21.74	1.40	0.11	14.25	252.60	1.72	4.53	62.77
Reservoirs:	**Alcorlo**	**Atance**	**Beleña**	**Castro**	**Entrepeñas**	**Gabriel y Galan**	**Rosarito**	**Tejera**				
Regulation cost (€/m3)	0.22	0.14	0.15	0.57	0.20	1.47	0.79	0.12				
Mean annual flow (m3/s)	2.20	0.40	3.40	0.38	17.60	27.80	24.20	1.00				
Regulation ind.	2.59	2.77	0.49	0.67	1.50	1.04	0.11	2.03				
Mean daily cost (1000€/day)	10.42	1.24	5.31	3.15	74.21	0.89	45.45	2.52				

4.2. Seasonality in Regulation Costs

This section assesses the statistical distribution of daily costs, i.e., differences in cost magnitude and differences in cost seasonality among dam regulation. In this study we differentiated three main groups in relation to the seasonality of the regulation costs which was based on the temporal distribution along the year of the ku coefficient.

The first group is composed by river reaches with high regulation costs mainly concentrated in summer (Figure 3). River reaches included in this group were Aguilar de Campoo, Barrios de Luna, La Magdalena, Las Cogotas, Santa Teresa, Riaño, Mansilla, Itoiz, El GradoI, Monteagudo, Alcorlo and Atance.

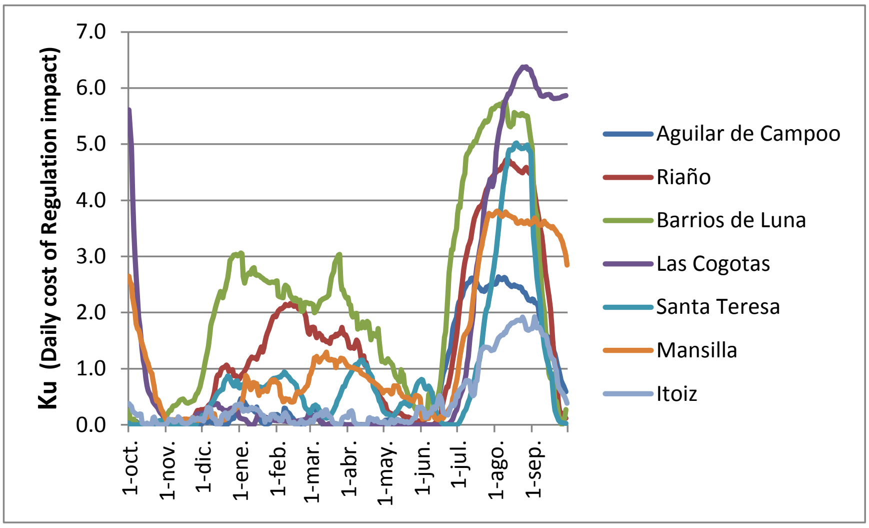

Figure 3. River reaches with summer maximum costs (Aguilar de Campoo, Barrios de Luna, La Magdalena, Las Cogotas, Santa Teresa, Riaño, Mansilla, Itoiz, El Gradol, Monteagudo, Alcorlo and Atance).

The second group is composed by river reaches with high regulation costs in summer and winter (Figure 4). River reaches included in this group were Requejada, Vegamian, Linares del Arroyo, Reinosa and Mediano.

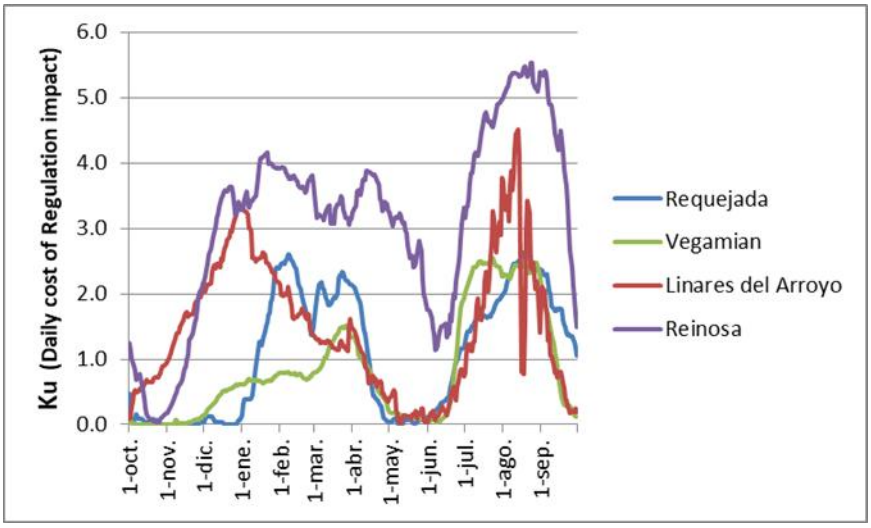

Figure 4. River reaches with winter and summer costs (Requejada, Vegamian, Linares del Arroyo, Reinosa and Mediano).

The last identified group is composed by river reaches with high regulation costs all along the year except in the spring, i.e., fall, winter and summer (Figure 5). River reaches included in this group were Almendra, Cernadilla, Oliana, Bubal, Ullivarri, Santolea, Castro, Gabriel y Galan, Rosarito and Tejera.

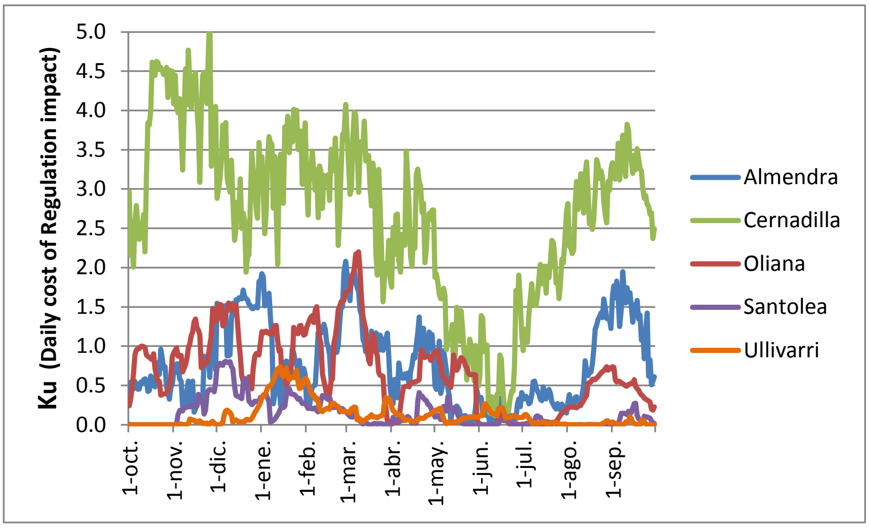

Figure 5. River reaches with fall, winter and summer costs (Almendra, Cernadilla, Oliana, Bubal, Ullivarri, Santolea, Castro, Gabriel y Galan, Rosarito and Tejera).

5. IMPLICATIONS AND CONCLUSIONS

This study has evaluated the environmental costs caused by large-dam flow regulation in 32 Spanish river reaches. The results of this study can be used by relevant stakeholders of freshwater use. Firstly, this study has addressed the question of how much water-users should pay for the recovery of environmental costs of flow regulation. Water managers may use the estimates proposed here as an example to assess environmental costs and stablish full cost recovery plans. Secondly, we have shown that some reservoirs cause much greater regulation costs than others. This means that water users of these environmentally expensive dams should justify that they are very profitable uses economically and / or socially very necessary. Lastly, we have shown that environmental costs change along the year due to water demand and environmental requirements, with seasons of peak costs that may be reduced. This gives an opportunity to improve dam management. Dam operators should be aware of it, be vigilant during these periods and design a flow-release system able to maximize economic benefits and minimize environmental impacts.

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