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# Water pricing: are 'polluters' paying the environmental costs of flow regulation?

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## Abstract

River ecosystems are severely affected by dams and reservoirs. The Water Framework Directive states that polluters should be financially responsible for the caused environmental damage. Nevertheless, the environmental costs associated to flow regulation often are not fully paid by water users. This study presents an approach to value the environmental costs of flow regulation based on the "polluter pays" principle, i.e., the amount to be paid should be proportional to the caused environmental impact. The procedure includes three major steps: (i) assessing the admissible range of regulated flow variability based on flow data during the pre-dam period, (ii) estimating the daily environmental impact of regulated flows according to the resulting hydrological change in terms of the intensity, duration and frequency of the impact, and (iii) calculating the environmental costs of flow regulation subject to spatiotemporal characteristics. This paper applies the proposed methodology in the Luna River, Spain. The advantages over other water cost valuation methodologies are discussed. The approach enlarges the current recognition of water environmental costs and represents a simple and practical management tool for achieving the objectives of the Water Framework Directive.

**Keywords:** Flow regulation, Environmental costs, Dams, Water, Water Framework Directive

## 1. Introduction

Water available for irrigation, hydroelectric production and urban or industrial supplies frequently requires flow regulation by dams and reservoirs which alters natural patterns of flow regimes and severely affects river ecosystems. At present, more than two thirds of river discharge that flows across the world is obstructed by more than 40,000 large dams. Vörösmarty *et al.* (2003) estimated that more than 50% of the sediment flow produced in watersheds is trapped in artificial reservoirs. Nilsson *et al.* (2005) found that the flow of water from reservoirs and reservoirs was one of the most frequent sources of environmental impacts in rivers (Poff *et al.*, 2007). The European Water Framework Directive (WFD) (2000/60/EC) was the first EU environmental legislation that explicitly required economic analysis of water use for assessing the level of recovery of water services and estimating the potential costs of restoration measures (Article 9. Annex III). Many attempts have been made in formulating methodologies and applications of economic principles to achieve the WFD environmental objectives (WATECO, 2003; Bithas *et al*., 2014; Babulo *et al*., 2011). However, environmental costs are usually the first costs that are not fully recovered, partially due to the complexity of nonmarket valuation. Despite there being numerous approaches assessing environmental costs based on revealed and stated people's preferences and production function (see Hanley and Barbier, 2009) they often do not estimate environmental costs proportionally to the impact. This is mainly because these approaches usually do not have a dynamic component that allows the cost to vary throughout time. This paper presents an approach to assess 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 (changes in river flow due to flow regulation).

## 2. Methodology

The methodological approach (see García de Jalón *et al.* (2017) for further information) is based on the "polluter-pays" principle, following the recommendations by the WFD. It allows estimating the environmental costs of flow regulation according to the human-induced environmental impact according to the inferred hydrological alteration (changes in magnitude, timing and duration of flows). The calculation procedure follows three major steps: (1) estimating the reference admissible range of variability based on the natural flow regime in the river reach; (2) quantifying the environmental impact due to differences between current circulating flows and their admissible range of variability; and (3) calculating environmental costs of these differences considering site (e.g. vulnerability or conservation status of the river reach) and seasonal (e.g. drought periods) characteristics.

### *2.1. Admissible range of flow variability*

The admissible range of flow regulation was defined on the basis of the river flow under natural conditions. The approach was based on the assumption that flow variability is an intrinsic attribute of the natural flow regime that should be preserved (Poff *et al*., 1997). The natural flow variability of the river was estimated using data from the non-regulated period (pre-dam period). Based on the range of daily flows along the year within the non-regulated period, an annual hydrograph can be characterized, and a reference area of flow variability may be devised, including daily-flow values between the 10- and 90-percentiles (see Figure 1). In order to define the reference range of admissible daily flow the percentiles 10 and 90 were selected. In case percentiles were not selected, the admissible range of variability would be too broad to quantify environmental impact or hydrologic alteration. For example, if under natural conditions the river dries up once every hundred years, we would assume that in that specific time of the year water regulators could dry up the river every year without producing any substantial environmental impact. Nevertheless, the selected percentiles are considered as subjective and they remain open to discussion. The reference range of flow variability was used to calculate the environmental impact of flow regulation. Thus, any variation of the daily flows within this range may be considered "admissible" and any variation out of the admissible range would be considered as an environmental impact. An exception to this should be low-frequency peak values associated to natural and extraordinary floods or droughts with long return periods. Although these flow disturbances can exceed the reference range we argue that they should not be considered environmental impact, as they occur under natural conditions and preserve the natural disturbance pattern of the flow regime with multiple environmental benefits (Bunn and Arthington, 2002).

### *2.2. Assessing the environmental impact of flow regulation*

The environmental impact was calculated for each year as the divergence between the currently circulating flows and the reference area of admissible flow variability. Thereby, the estimated environmental impact could be due to either discharges higher than the upper limit of the admissible area (High-flow impact) or discharges lower than the lower limit (Low-flow impact) (see Figure 2). Equation 1 and 2 quantify High-Flow and Low-Flow impacts ($HFI_{i,t}$ and $LFI_{i,t}$ respectively) of the river reach *i* in a time instant *t*. Both impacts were calculated as the distance from the high (90 percentile) and low (10 percentile) limits of the admissible area of discharges. In order to normalize the estimated *HFI* and *LFI* the subtraction between current flow (*CF*) and reference flow was divided by the maximum flow value. In the case of *HFI*, the maximum flow value corresponds to the current flow and in the case of *LFI* the maximum is the low reference flow.

$$HFI_{i,t} = \frac{CF_{i,t} - HRF_{i,t}}{CF_{i,t}} \qquad (1)$$

$$LFI_{i,t} = \frac{LRF_{i,t} - CF_{i,t}}{LRF_{i,t}} \qquad (2)$$

Where HRF indicated the upper limit of the reference area of admissible flows (percentile 90 of the reference flow) and LRF indicated the lower limit of the reference area (percentile 10 of the reference flow). In the assessment of the impact of hydrologic alteration not only changes in the magnitude and timing of flows were considered but also their duration. For instance, the potential impact of maintaining same released flow values during relatively a long period but within the range of admissible variability. For this purpose, moving averages of daily discharges for three, seven and thirty consecutive days were calculated. High-flow and Low-flow impacts were calculated as the average of the previously estimated High-flow and Low-flow impacts for one, three, seven and thirty days. Finally, the environmental impact of flow regulation was calculated as the sum of these average values of High-flow and Low-flow impacts.

### *2.3. Estimating the environmental costs*

Following the "polluter-pays principle" (i.e., "regulator-pays principle), environmental costs were calculated as a function of the environmental impact. Thus, the price that water users should pay for the recovery of environmental costs of flow regulation should be proportional to the caused impact. The environmental costs were calculated following Equation 3:

$$EC_{i,t} = EI_{i,t-1}\ \mu_{i,t-1} \qquad (3)$$

where $EC_{i,t}$ represents the environmental cost that water users should pay per unit of water (e.g., € $m^{-3}$) for using regulated water available at a time instant *t* at a river reach *i*. The environmental cost in a time instant *t* (i.e. day) was calculated as the product of the environmental impact (*EI*) in the previous time instant (i.e. t-1 or the day before) and the coefficient $\mu$ which was measured in euros per cubic meter of released water. The coefficient $\mu$ transformed environmental impact (i.e., flow deviations) into environmental costs (e.g., € $m^{-3}$). This coefficient can take different values for different rivers or reaches as well as for different years or time of the year. Moreover, the relationship between environmental costs and impacts can be considered to be directly proportional or exponential, i.e., the costs increase exponentially as the environmental impact increases. Equation 4 shows how $\mu$ was estimated in this study:

$$\mu_{i,t} = a_{i,t}\ \exp^{b_{i,t}\ EI_{i,t}} \qquad (4)$$

where 'a' (e.g., € $m^{-3}$) was a coefficient that can vary according to natural water availability in the specific year and other socio-economic parameters such as the actual price that water users currently pay; and 'b' was a unit-less coefficient that determined the exponential relation between environmental costs and impacts. 'b' represents the relative vulnerability or conservation level of the river-reach and takes the value 0 when the minimum value of vulnerability or conservation interest is assumed. Different 'b' values could be applied according to the desired environmental status of the river reach and season of the year. For instance, high values should be used during spawning season of endangered migration species like salmon or sturgeon.

## 3. Results: an example in the Luna River

A case study in the Luna River, tributary of the Duero River, NW Spain, was used to show the applicability of the approach. The study site corresponds to the Barrios de Luna Dam. Figure 1 shows the estimated admissible range of flow variability in the Luna River during the pre-dam period (1913-1945). The smoothed dark-green line

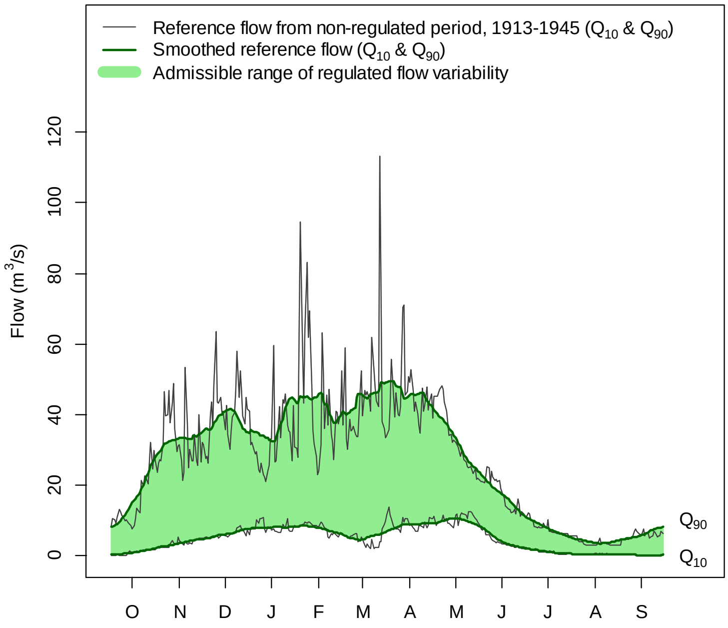
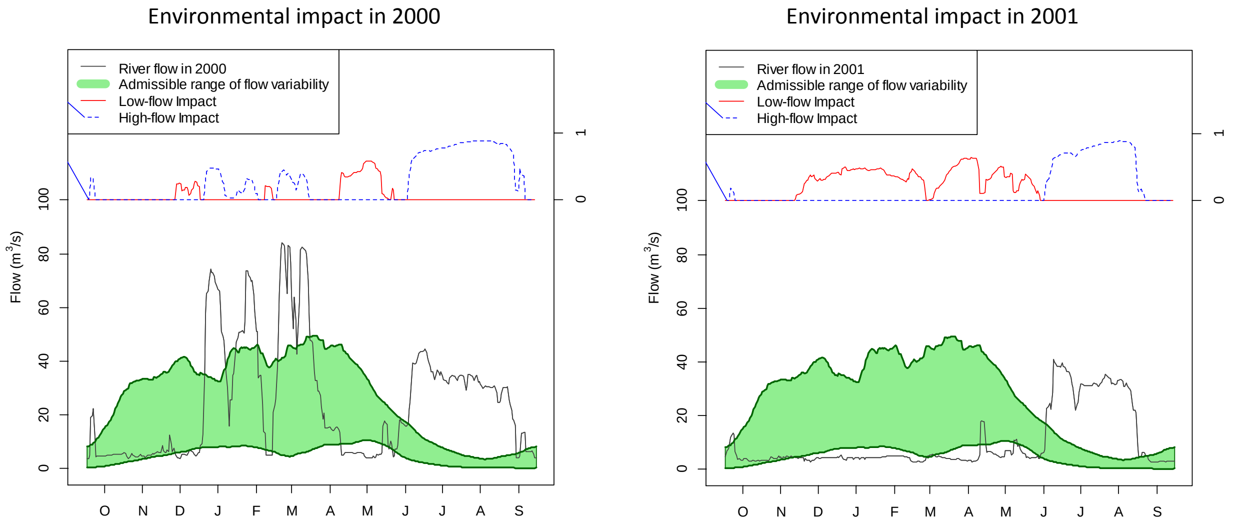


**Figure 1.** Admissible range of regulated flow variability for the Luna River based on non-regulated flow data (1913-1945). The light-green area shows the admissible range of regulated flow variability, the black line shows the 10th and 90th percentiles during the pre-dam period, and the dark-green line shows the smoothed upper and lower limits calculated by a moving average with 30 lags (days)**.**


Environmental impact in 2000

Environmental impact in 2001

**Figure 2.** Estimation of *Low-flow* and *High-flow* impacts of flow regulation in the Luna River in 2000 (left graph) and 2001 (right graph). The lower graph shows the circulating flows (black line) over the estimated reference admissible range of flow variability (light-green area). The upper graph shows the estimated *Low-flow* (dark-green solid line) and *High-flow* (blue dashed line) impacts calculated as the deviation from the reference admissible area.

corresponding to the 10th percentile of daily flows broadly covers the fluctuation of minimum flows whereas the line corresponding to the 90th percentile eliminated from the admissible range a much wider range of natural fluctuations in maximum flows. Nevertheless, when considered together they represent the complete natural flow variability of the river reach, reflecting the magnitude, timing and variability of the average natural daily flows. The environmental impact of regulated flow (lower or higher than the admissible range) is presented in Figure 2. In the Luna River, flow regulation is mainly for irrigation in the Páramo Leonés region. The environmental impacts are seasonal which are primarily concentrated in winter due to lower flows (water storage period) and in summer due to higher flows (irrigation period). In 2000 (left graph), there were four extraordinary high flows January and April associated with high rainfall natural events. Despite being well above the upper limit of the admissible range the events resulted in small high-flow-environmental impacts. This was explained due to the relatively short duration of the peak-flow. In contrast, deviations responding to regulation patterns lasted for much longer periods, and they resulted in much higher low-flow impacts between November and April and in high-flow impacts from June to September. In 2001 (right graph), there were no extraordinary high flows. Large low-flow impacts were caused between late November and early June. Figure 3 presents the estimated environmental costs of flow regulation in 2000 and 2001 under various scenarios. It shows the fluctuation in environmental costs under different values of the coefficient ‘a’ and ‘b’ in Equation 4. From mid-November to June the environmental costs are caused due to low-flow impact. On the contrary, from June to September the environmental costs are produced due to high-flow impacts.

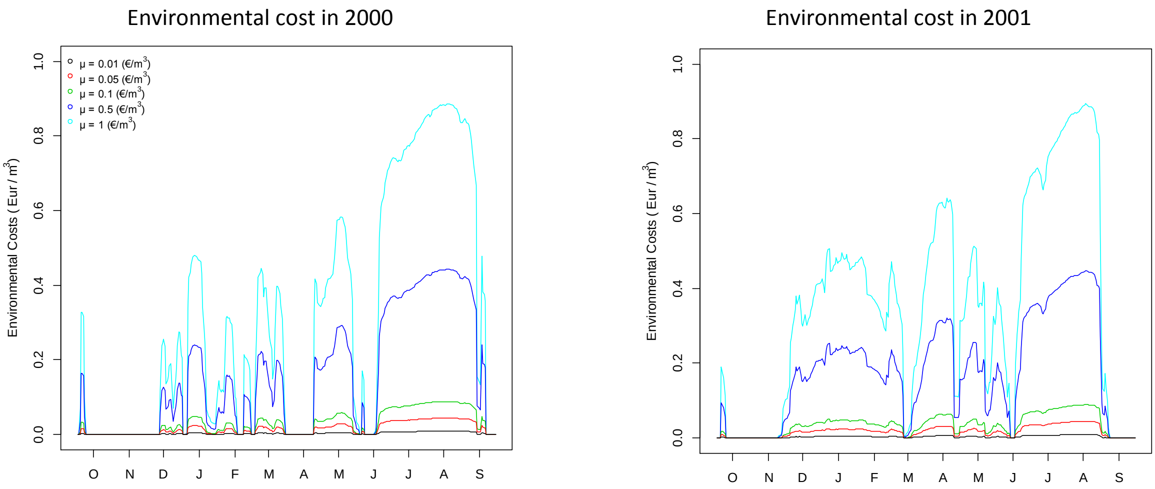


**Figure 3.** Daily environmental costs of 2000 and 2001 regulated flow considering different values of the coefficient μ, which includes different weights of river vulnerability, conservation status, or other special constraints.

## 4. Discussion

One of the potential improvement to be made in our approach is to quantify impacts produced by the alteration of flow rates of change. For instance, as long as a hydrograph lays within the two margins of the admissible range of regulated flow variability, the impact would remain unquantified. However, a natural short term flow variability should be maintained in order to sustain relevant hydromorphic and ecological processes in stream ecosystems. On the opposite end of these impacts, extreme flow variation will yield no impact as long at local peaks remain within the admissible range of variation. Inter-day flow variation due to differential hydropower demand along the week would be an example of such impacted schemes. All in all, the field of perspectives of our approach is wide. And it can be addapted to other uses of water resources, such as chemical or thermal impacts, as long as their natural variability can be measured.

## 5. Conclusions

The proposed methodology represents an innovative attempt to evaluate the environmental costs of flow regulation by dams and reservoirs, which up to date are not included in the proposed cost recovery methodologies. The method is based on the “polluter-pays” principle and presents several advantages in relation to previous approaches based on people’s preference and production functions. It can be used as a dynamic indicator of the hydrological alteration, allowing a clear visualization of the potential impacts and costs of the flow regulation. The results in the Luna River in 2000 and 2001 exemplify numerous rivers in the Mediterranean region. The approach could help facilitate communication and discussion among water actors. It can help optimize the appropriate time of the year for water releases from the dam, by minimizing the environmental cost and or maximising profitability of water use. In the same way, the approach could work as a mechanism of self-control to avoid further degradation when regulating flows.

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