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FlowRegEnvCost: An R package for assessing the environmental cost of river flow regulation

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Abstract

FlowRegEnvCost is a contributed R package for assessing the environmental costs of river flow regulation. The analytical methods of FlowRegEnvCost include 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. The approach is based on the "polluter pays" principle; that is, the amount to be paid should be proportional to the resulting environmental impact. This paper applies FlowRegEnvCost to the Esla River, in Spain. FlowRegEnvCost 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: FlowRegEnvCost; R; library; Flow regulation; Dams; Water Framework Directive

Highlights

- FlowRegEnvCost is an R package for assessing the environmental costs in rivers
- A methodology to assess the daily environmental costs of flow regulation is developed
- The polluter-pays principle is applied proportionally to hydrological alterations
- The flexibility and simplicity of the approach make it a practical management tool
- The Water Framework Directive encourages the full cost recovery of water services

1. Introduction

Making 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. Flow regulation by dams has been considered to be one of the most frequent sources of environmental impacts on rivers (Nilsson et al. 2005). Despite wide recognition of the impact of flow regulation, its environmental costs are not quantified. Consequently, full cost recovery is not achieved, partially because of the complexity of measuring and valuing the dynamics of environmental impacts (WATECO 2003; Bithas 2008; Babulo et al. 2011).

This paper presents FlowRegEnvCost, an R package, to assess the specific environmental costs of flow regulation based on the intensity of the hydrological alteration of the natural flow regime. FlowRegEnvCost uses a dynamic water pricing approach, which is determined by the hydrologic alteration the river suffers at every time step (changes in river flow due to flow regulation).

2. Structure and functions in FlowRegEnvCost

The methodological approach is based on the "polluter pays" principle, following the recommendations by the Water Framework Directive (WFD). FlowRegEnvCost includes various functions that allow for estimating the environmental costs of flow regulation, according to the human-induced environmental impact of the inferred hydrological alteration (changes in magnitude, timing, and duration of flows). These functions can be divided into three categories: (i) loading river flow data, (ii) generating tabular results, and (iii) generating graphical results.

2.1. River flow data

Flow data need to be loaded onto R to run any function in FlowRegEnvCost. The loaded data should be an "R data frame" in which the first column is the date (*column name: Date*) and the second column is the mean daily flow measured in the gauging station (*column name: Flow*). The loaded data should be called "flowdata". The date format needs to be date, month, year (DMY) with a stroke (slash) "/" separating the date components (dd/mm/yyyy). The FlowRegEnvCost package provides river flow data from the Esla River (Spain) as an example.

2.2. Functions for generating tabular results

The procedure for calculating the environmental costs of flow regulation is separated into three functions: (i) estimating the reference admissible range of variability, based on the natural flow regime in the river reach (*adm_range*); (ii) quantifying the environmental impact due to differences between current circulating flows and their admissible range of variability (*impact_reg)*; and (iii) calculating environmental costs of these differences considering site attributes (e.g., vulnerability or conservation status of the river reach) and seasonal characteristics (e.g., drought periods) (*daily_cost).*

2.2.1. adm_range: Calculates the admissible range of flow variability

Calculating the admissible range of flow variability is the first step towards estimating the environmental cost of flow regulation. In FlowEnvRegCost, the admissible range is defined on the basis of the river flow under natural conditions. This approach is 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 is calculated using data from the non-regulated period (pre-dam period). Based on the range of daily flows within the non-regulated period, an annual hydrograph can be characterized. In this way, a reference of admissible daily flows can be devised, including daily flow values between the 10th and 90th percentiles (see Figure 1). The selection of a percentile value is necessary to quantify hydrologic alteration. Otherwise, the admissible range would be too broad, and some daily environmental impacts would not be measured. For example, if under natural conditions the river reach dries up once every fifty years, it would be assumed that on that specific day of the year, water regulators could dry up the river every year without producing any significant environmental impact. Nevertheless, the selected percentiles may be considered flexible and open to change.

The reference range of flow variability is used to estimate the environmental impact of flow regulation. Thus, when the variation of the daily flows is within this range, the regulated flow may be considered “admissible”. On the other hand, when the variation is outside the admissible range, the regulated flow may cause an environmental impact. An exception to this rule should be low-frequency peak values associated with 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 as likely to cause an environmental impact because they occur under natural conditions and preserve the natural disturbance pattern of the flow regime, with multiple environmental benefits (Bunn and Arthington 2002).

2.2.2. impact_reg: Calculates the daily environmental impact of flow regulation (high- and low-flow impact)

FlowEnvRegCost calculates the environmental impact as the divergence between the currently circulating flow and the reference area of admissible flow variability. The estimated environmental impact could thereby be caused by discharges lower than the lower limit of the admissible area (low-flow impact) or by discharges higher than the upper limit (high-flow impact) (see Figure 2).

Equations 1 and 2 calculate low-flow and high-flow impacts ($LFI_{i,\mathrm{t}}$ and $HFI_{i,\mathrm{t}}$ respectively) of the river reach i in a time step t. In both cases, impacts are estimated as the distance from the low (10th percentile) and high (90th percentile) limits of the admissible area of discharges. To normalize the estimated HFI and LFI, relative change values are used. Thus, the absolute difference between current flow (CF) and reference flow is divided by the maximum flow value. In the case of LFI, the maximum flow value corresponds to the low reference flow; whereas in the case of HFI the maximum is the current flow.

$$\acute{z}/I_{i,\sim} = \frac{\acute{z}R/_{i,\sim} - C/_{i,\sim}}{\acute{z}R/_{i,\sim}} \qquad (1)$$

$$\oint / I_{i,\sim} = \frac{C/_{i,\sim} - \oint R/_{i,\sim}}{C/_{i,\sim}} \quad (2)$$

where *LRF* indicates the lower limit of the reference area of admissible flows, and *HRF* the corresponding upper limit.

In the assessment of hydrologic alteration, not only changes in magnitude and timing of flows are considered but also their duration. FlowEnvRegCost calculates the moving averages of daily discharges for three, seven, and thirty consecutive days. Low-flow and high-flow impacts are calculated as the average of the previously estimated low-flow and high-flow impacts for one, three, seven, and thirty days.

2.2.3. *daily_cost*: Calculates the daily environmental costs of flow regulation

Following the "polluter pays" principle (i.e., regulator pays principle), environmental costs are calculated in FlowEnvRegCost as a function of their corresponding environmental impact. Thus, the price that water users should pay for the recovery of environmental costs of flow regulation should be proportional to the resulting impact. The environmental costs are calculated in Equation 3:

$$\oint \Diamond C_{i,\sim} = \oint / I_{i,\sim\_1}\ \mu_{i,\sim\_1} \quad (3)$$

where $HEC_{i,t}$ represents the environmental cost caused by high flows that water users should pay per unit of water (e.g., € m^{-3}) for using regulated water available at a time step *t*, at a river reach *i*. The environmental cost in time step *t* (i.e., a day) is calculated as the product of the high-flow impact (*HFI*) in the previous time step (i.e., t-1 or the day before) and the coefficient μ which is measured in euros per cubic metre of released water. The same approach is used to calculate the environmental cost caused by low flows ($LEC_{i,t}$).

The coefficient μ transforms the 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 seasons. 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 μ is estimated in FlowRegEnvCost:

$$\mu_{i,\sim} = \acute{A}_{i,\sim} \exp^{b_{i,t}\ EI_{i,t}} \quad (4)$$

where *a* (e.g., € m^{-3}) is 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* is a unit-less coefficient that determines the exponential relationship between environmental costs and impacts. The coefficient *b* represents the relative vulnerability or conservation level of the river reach and takes the value 0 at the minimum value of vulnerability or conservation interest. Different *b* values can be used according to the desired environmental status of the river reach and season of the year. For example, high values should be used during the spawning season of endangered migrating species such as salmon or sturgeon.

2.2.4. *summary_flow*: Provides a summary of flow data during the pre-impact period

summary_flow calculates the mean and 0, 10, 25, 50, 75, 90, and 100 percentiles of all days of the previous years of the human-induced impact.

2.3. Functions for generating graphical results

FlowEnvRegCost has four functions to show graphical results of the admissible range of flow variability (*adm_range_plot*), high- and low-flow environmental impacts of flow regulation (*impact_reg_plot* and *impact_reg_multi_plot*), and daily environmental costs (*daily_cost_plot*):

2.3.1. adm_range_plot: Plots the admissible range of flow variability (see Figure 1)

2.3.2. impact_reg_plot and *impact_reg_multi_plot*: Plot the daily environmental impact of flow regulation (high-flow and low-flow impact) for single and multiple years (see Figure 2)

2.3.3. daily_cost_plot: Plots the daily environmental costs of flow regulation (see Figure 3)

3. A case study of the Esla River

A case study of the Esla River, tributary of the Duero River, northern Spain, was used to show the applicability of FlowRegEnvCost. Data have been available since 1964 on the Esla River at the Riaño Dam. The dam has operated since 1988. FlowRegEnvCost provides the flow data for this example.

Figure 1 shows the estimated admissible range of flow variability during the pre-dam period. The smooth red line, corresponding to the 10th percentile of daily flows, broadly covers the fluctuation of minimum flows, whereas the line corresponding to the 90th percentile eliminates from the admissible range a much wider range of natural fluctuations in maximum flows. Nevertheless, taken together these lines represent the complete natural flow variability of the river reach, reflecting the magnitude, timing, and variability of the average natural daily flows.

< FIGURE 1 >

The environmental impact of regulated flow (lower or higher than the admissible range) is presented in Figure 2. In the Esla River, flow regulation is intended mainly for irrigation, and consequently, the environmental impacts are seasonal and concentrated in the winter due to lower flows (a water storage period) and in the summer due to higher flows (an irrigation period). The figure shows a great difference in the environmental impact between two consecutive years in the pre-impact period (1966 and 1967) and in the post-impact period (2009 and 2010).

It is worth highlighting that in the case of extraordinary high flows associated with rainfall, despite being well above the upper limit of the admissible range, the events resulted in small high-flow environmental impacts. This can be explained by the relatively short duration of the peak flow. In contrast, deviations responding to regulation patterns lasted for much longer periods, resulting in much higher low-flow impacts between November and April and in high-flow impacts from June to September.

< FIGURE 2 >

Figure 3 shows the estimated environmental costs of flow regulation in 2010. In this example, the coefficient *a* in low-flow impacts *($a = 0.05$)* was higher than in high-flow impacts *($a = 0.01$)*. From mid-November to May, the environmental costs are caused mainly by low-flow impacts. In contrast, from June to September, the environmental costs are produced by high-flow impacts.

< FIGURE 3 >

4. Conclusions

FlowRegEnvCost represents an innovative attempt to evaluate the environmental costs of flow regulation by dams and reservoirs, that to date have not been included in proposed cost recovery methodologies. The method is based on the "polluter pays" principle and presents several advantages compared to approaches that are based on stated or revealed preference methods and production functions. It can be used as a dynamic indicator of the hydrological alteration, allowing for a clear visualization of the potential impacts and costs of the flow regulation. The results on the Esla River represent numerous rivers in the Mediterranean region.

Although FlowRegEnvCost could serve for a wide range of flow regulation scenarios, there are various potential ways to improve the methodology. For instance, as long as a hydrograph is positioned within the two margins of the admissible range of regulated flow variability, the impact will 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 variations will have no environmental impact as long as local peaks remain within the admissible range of variations. Inter-day flow variations due to differential hydropower demands during the week are an example of such impacted schemes. All in all, the scope for implementing our approach is wide. Additionally, the method can be adapted to other uses of water resources that induce different impacts, such as chemical or thermal impacts, as long as the natural variability of such uses can be measured.

The river discharge input data can be downloaded from numerous sources, e.g., the National Water Information System of the U.S. Geological Survey, the National River Flow Archive in the United Kingdom, or the website of each River Basin District in Spain. Further improvements will be proposed to link FlowRegEnvCost to interoperable services "on the fly" so that end-users will not necessarily need to provide river discharge data except to select a data provider. It is also possible to develop a graphical user interface (GUI) using OpenCPU (Ooms 2014), which will in turn facilitate model usability for those unfamiliar with R.

FlowRegEnvCost aims to 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 maximizing the profitability of water use. In the same way, FlowRegEnvCost could operate as a self-control mechanism for avoiding further degradation of flow regulation.

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Code metadata

Current code version	v 0.1
Permanent link to code/repository used for this code version	https://github.com/garciadejalon/FlowRegEnvCost
Legal Code License	MIT
Code versioning system used	Git
Software code languages, tools, and services used	R
Compilation requirements, operating environments & dependencies	64-bit operating system & R environment version 3.2.3 and up (64-bit) & R packages: zoo
If available Link to developer documentation/manual	https://github.com/garciadejalon/FlowRegEnvCost/blob/master/man/FlowRegEnvCost.pdf
Support email for questions	s.garciadejalon@gmail.com

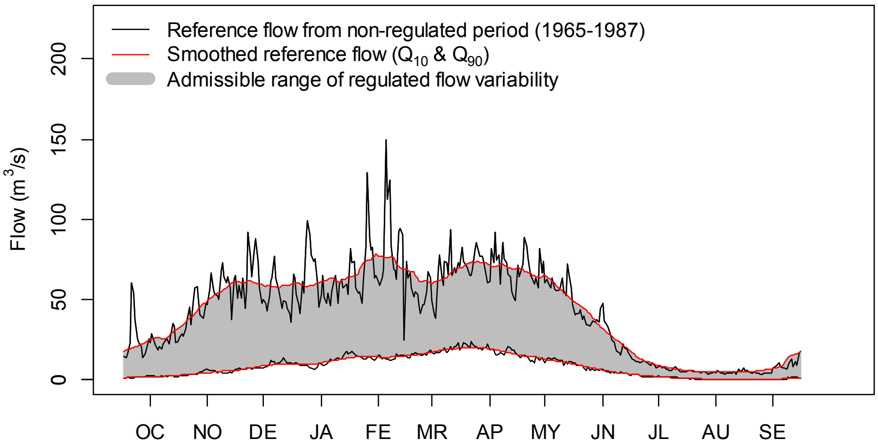

Figure 1. Admissible range of flow variability for the Esla River, based on non-regulated flow data (1964-1987). The grey area shows the admissible range of flow variability, the black line shows the 10th and 90th percentiles during the pre-dam period, and the red line shows the smoothed upper and lower limits calculated by a moving average with 30 day lags.

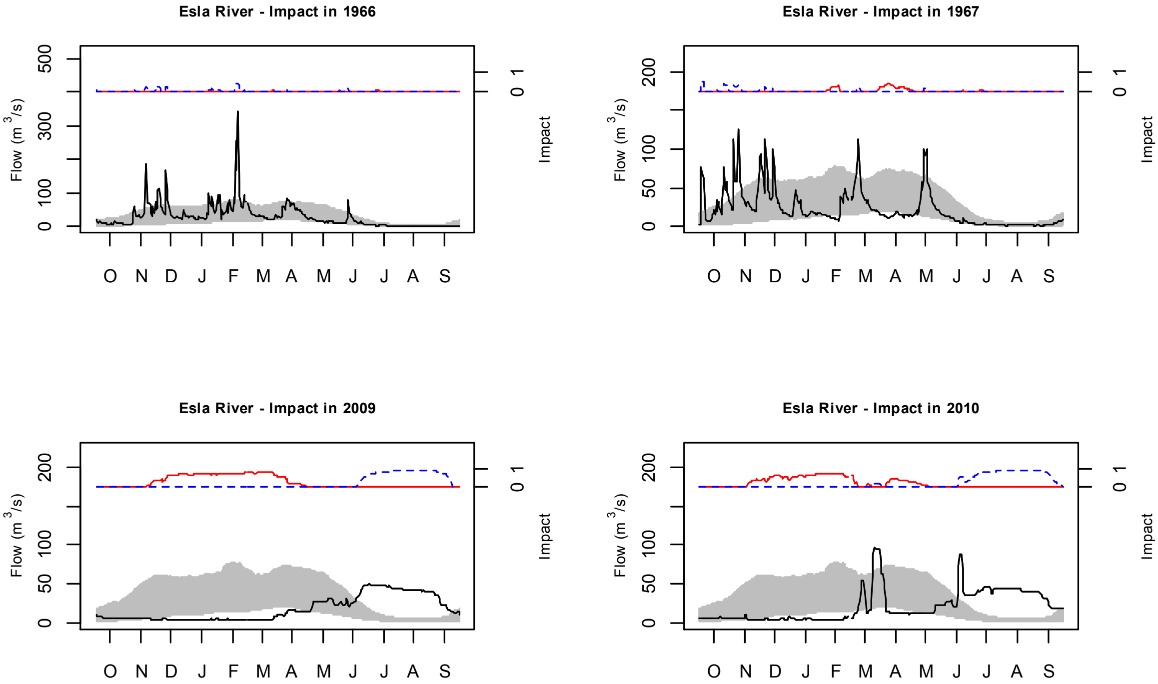

Figure 2. Estimation of low-flow and high-flow impacts of flow regulation in the Esla River in two consecutive years during the non-regulated period (1966 and 1967) and in the regulated period (2009 and 2010). In each figure, the lower graph shows the circulating flow (black line) over the estimated admissible range of flow variability (grey area). The upper graph shows the estimated low-flow (red solid line) and high-flow (blue dashed line) impacts, calculated as the deviation from the reference admissible range.

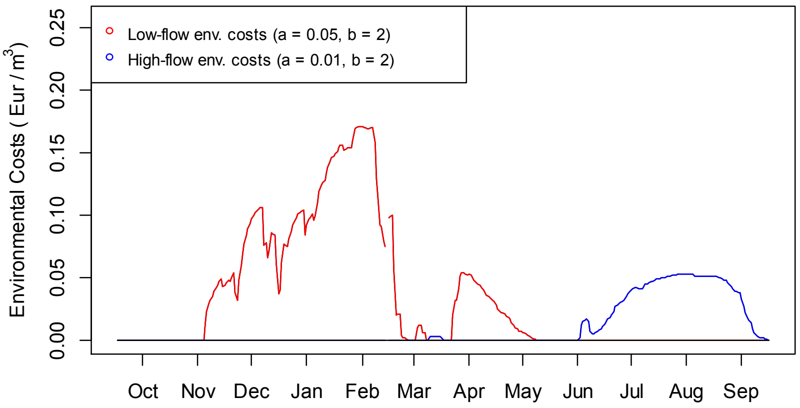

Figure 3. Estimated daily environmental costs in the Esla river in 2010