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The natural variability approach. Application to the analysis of the hydrologic alteration in five rivers (Ebro basin, Spain)

Abstract

Increasing flow regulation in the recent decades in Spain has produced a significant change in flow regimes in most of the Spanish rivers. In this study a refined methodology is applied to the analysis of the hydrologic alteration in five fluvial stretches affected by flow regulation in the Ebro river basin. The work is based on the same group of parameters proposed by other methods (Richter et al., 1997; Black et al., 2005) that measure hydrologic alteration, but our approach synthesizes the information, and values the gravity of the present alteration, in terms of the magnitude (severity) and frequency of the impacts in each river. The severity of the alterations in a time series is measured through two proposed new metrics which simplifies the information and makes their interpretation easier and the identification with specific water use that produces the alteration.

The application of this metrics in the five case studies offered consistent results and a good characterization of the alterations in each case. The results show that the magnitude of the alterations is more severe on the northern tributaries of River Ebro (affected by hydroelectric production) than on the southern ones, where the purposes of the regulation are water supply and irrigation. The proposed methodology proved to be useful and accurate in the classification of the degree of hydrologic alteration under different management schemes. In this way, they can also serve as a basis for the estimation of the economic value produced by the loss or deterioration of the environmental services associated with these ecosystems.

Keywords: ecohydrology, streamflow, frequency, natural variability, environmental valuation.
JEL Classification: Q25.

Introduction

The need to regulate flows on Spanish rivers in order to satisfy water supply demands has led to the construction of a large number of hydraulic engineering infrastructures. There are currently more than 1000 large dams in the national hydrographic system, making Spain one of the countries with the greatest number of dams and setting it at the head of the world ranking in terms of number of dams per inhabitant. The abundance of these structures gives an idea of the extent to which Spanish fluvial systems have been altered, and in most regions it is practically impossible to find river stretches without human intervention; as is the case in the province of Madrid (Heras, 1999).

Among the effects caused by dams and reservoirs, the main one is the alteration of the flow regime. Although each use gives rise to different disruptions of the flow regime, in most cases the general effect is a reduction and lamination of floods. However, changes also affect parameters of biological importance, leading to severe alteration of processes that are determined by the volume of water flowing in the river and loss of the complexity and the richness of the populations that these ecosystems support.

This situation has stimulated several lines of research, most of which are focused on: (1) the analysis of the effects of flow alteration on the fluvial system with emphasis on biological communities; (2) the identification of water management solutions that balance the use of water and the conservation of ecosystems; or (3) the assessment of the degree of alteration of fluvial systems as a result of flow regulation. In the latter case it is firstly necessary to characterize the natural flow regime of each river before deepening in the research of methods to evaluate human-driven alteration.

This is the aim that has been pursued in the study of streamflow regimes on five river stretches in the Ebro basin (north-eastern Spain) which results are reported in this paper. The analysis of flow regimes has been performed using the method described by Richter et al. (1997), based on the comparison of the flows recorded in two periods, before and after regulation, in order to verify whether the flow indicators found after regulation are within a certain range that may be considered natural.

After determining what regimes are altered and to what extent, the study goes on to propose a classification of the severity of the alterations measured on each stretch (Richter's method only identifies the alteration) and a way of estimating their economic impact and internalization in the productive systems.

Historic flow records have been used to calculate a series of hydrologic indices that define the flow regime on each river in terms of magnitude, timing, frequency, duration and rate of change. To compare the alteration with the former situation, a natural variability range (NVR) has been calculated, determining the rate within which each index varies in natural conditions. The severity of the alteration is measured by calculating how often and how far the new values for each index exceed the NVR, and this information is used to classify the alterations on each river.

In view of the fact that these alterations are produced by human activities which generate economic benefits, and that environmental costs have hitherto not been accounted for in the businesses that benefit from these resources, a number of ideas are put forward which seek to calculate the economic value of the alterations and to incorporate them in a management model that more harshly penalizes actions which cause the greatest divergence from the considered natural pattern. Since the aim of such a method would be to improve the ecological status of these rivers, the possible economic sanction should lead to reconsideration of the way in which flow releases from the dams are programed, taking into account the damage caused to the environment. All of this should help to assure that future releases are made with more biological sense, adapting the altered regimes as far as possible to the natural regimes that are the basis for the maintenance of the biodiversity, structure and functioning of these rivers.

1. Methodology

1.1. Area of study. The studied stretches are situated on the rivers Gállego, Aragón, Segre, Guadalope and Jalón, all of which belong to the Ebro basin hydrographic system (north-eastern Spain, figure 1). The analysis has been carried out using daily flow data from five gauging stations (Cedex, 2002) situated downstream of the regulating infrastructures that affect the natural regimes of these rivers. Only stations with available data for at least 20 years prior to regulation (natural regime) and 20 years after regulation were selected for this study. Regulation is considered to start upon the placement in service of the oldest dam (see Table 1), although in most cases other dams have subsequently been built which further complicate the problem. An attempt has been made to include a set of rivers with a certain hydrological variability among them. The analyzed stretches include three left-bank rivers, which are Pyrenees mountain rivers, and two right-bank rivers, one of which (Jalón) has its upper reaches in an area of Mesozoic limestones that constitute an excellent aquifer which gives rise to a highly regular natural regime (Table 1)

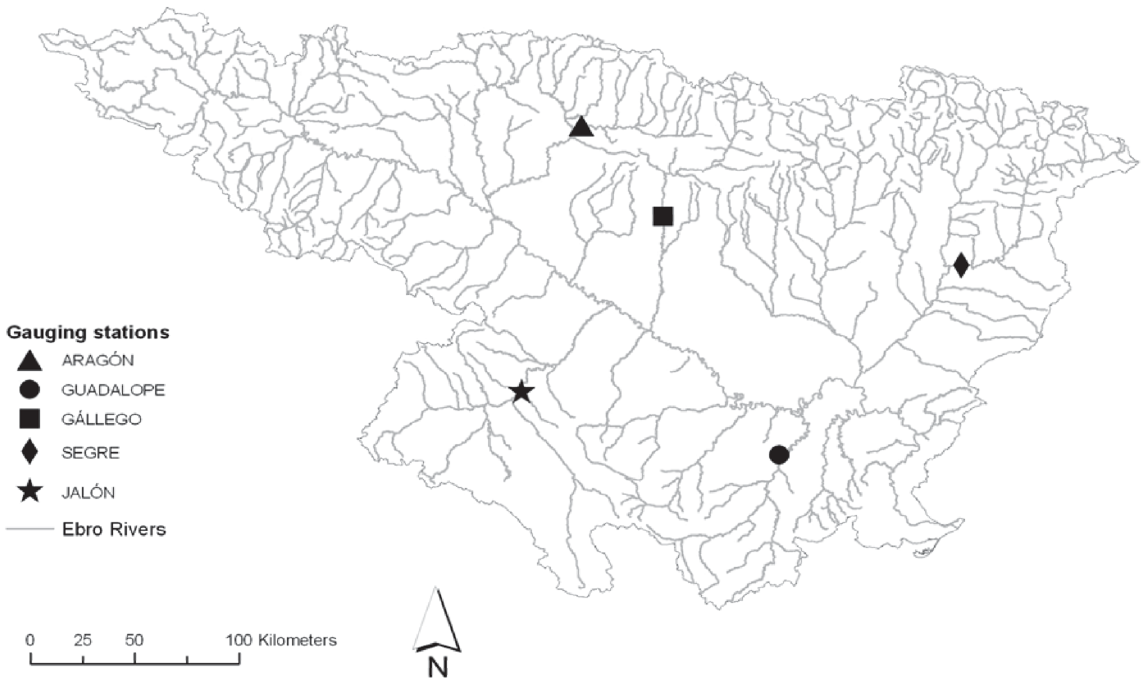


Fig. 1. Ebro basin with location of gauging stations where data was collected

Table 1. Main characteristics of studied river stretches, gauging stations and affecting dams

River	Mean flow (m^3/s)	Basin area (km^2)	Gauging station	Oldest dam and year of construction
Gállego	21.51	2167.91	Ardisa (12)	Bubal 1971
Aragón	30.73	2273.44	Yesa-PP (101)	Yesa 1960
Segre	25.03	3861.35	Alos de Balaguer (104)	Oliana 1959
Guadalope	5.42	3359.51	Alcañiz (15)	Santolea 1932
Jalón	13.05	7638.35	Huermeda (9)	LaTranquera 1960

In order to ensure the comparability of the data on all the rivers, daily flow records have been taken for 20 years before regulation and 20 years after regulation.

1.2. Assessment of hydrologic alterations. As mentioned above, the methodology of Richter et al. (1997) has been followed. Thirty-two hydrologic parameters (Table 2) are calculated for 20 years prior to regulation, in order to characterize the natural flow regime, and for 20 years after regulation, once the regime has been modified. In order to determine the NVR the mean value and standard deviation of each parameter for the 20 years prior to regulation are obtained, and the NVR is established as the interval resulting after respectively adding and subtracting the standard deviation from the mean value.

Table 2. Hydrologic indices used in the IHA (index of hydrological alteration) method and their characteristics (after Richter et al., 1996)

Statistical group	Hydrologic parameter
Group 1: Magnitude of monthly water conditions	Mean flow for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Mean 1D-Min (Annual minima 1-day means)
	Mean 1D-Max (Annual maxima 1-day means)
	Mean 3D-Min (Annual minima 3-day means)
	Mean 3D-Max (Annual maxima 3-day means)
	Mean 7D-Min (Annual minima 7-day means)
	Mean 7D-Max (Annual maxima 7- day means)
	Mean 30D-Min (Annual minima 30-day means)
	Mean 30D-Max (Annual maxima 30-day means)
	Mean 90D-Min (Annual minima 90-day means)
	Mean 90D-Max (Annual maxima 90- day means)
Group 3: Timing of annual extreme flows	Date of each annual 1-day minimum flow
	Date of each annual 1-day maximum flow
Group 4: Frequency and duration of high and low flows	Number of high flows each year
	Number of low flows each year
	Mean duration of high flows within each year (days)
	Mean duration of low flows within each year (days)
Group 5: Rate and frequency of trend changes	Means of all positive differences between consecutive daily values
	Means of all negative differences between consecutive daily values
	Annual number of flow increases
	Annual number of flow decreases

As can be seen in Table 1, these indices are classified into 5 groups known as the main flow regime components (Lytle and Poff, 2004), describing the magnitude, timing, frequency, duration and variability range of the studied flows.

Once the reference NVR values are established for each parameter, a three-step check is made of the situation on each river. Firstly it is checked whether any alterations have occurred; then the severity of the alterations is evaluated; and finally these results are used to classify the alterations according to their severity and frequency.

To determine whether the regimes have suffered any alteration it is seen whether the values of the indices in the years with the modified regime are within the NVR or whether they are outside this margin of tolerance. The latter situation is considered to indicate an alteration caused by human intervention in the functioning of the regime component described by that parameter.

When the existence of an alteration is verified, its severity is then measured, assessing the magnitude of deviation from the NVR and the frequency of the deviation. If the new value exceeds the NVR by just a few units, the alteration is considered to be less severe than if it doubles or triples the NVR limit value. On the other hand, the alteration is also considered to be much more severe if it occurs with great frequency.

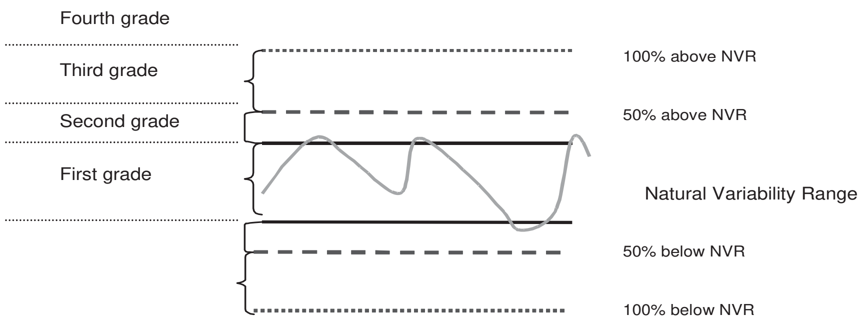
To establish categories of the severity of alterations using different criteria, a number of strategies may be followed, e.g., measuring the number of affected parameters on each river; the number of years that the alteration occurs; or the intensity of the alteration, i.e., the magnitude of the difference between the value obtained and the limits of the NVR.

Following these rules, the assessment of alterations can address two different aspects. The first focuses on the magnitude of the alteration, considering how far the current value of the intervened regime varies from values within the NVR, while the second evaluates the frequency of the alteration, considering how often or how many years the value of a particular hydrological parameter exceeds the NVR.

In the first case, the mere fact that a parameter exceeds the NVR signifies an alteration, although its severity will depend on how far it varies from the maximum or minimum NVR value.

In order to classify the alterations by the degree of their severity, two new ranges of values are defined to measure to what extent the parameters are modified. The thresholds of these ranges are percentage values above and below the upper and lower limits (e.g., 50% and 100% above the upper limit).

These thresholds allow the alterations to be classified in four grades of severity, according to the magnitude of the parameter values in the intervened regime. The first grade includes the parameter values that are within the NVR; the second grade includes the values that are outside this range but do not reach severity threshold 1; the third grade contains the parameter values that are between severity thresholds 1 and 2; and the fourth grade is when the magnitude of the parameter values surpasses severity threshold 2. To illustrate this idea, the severity thresholds are depicted in Figure 2 along with the grades corresponding to the intermediate areas between them.



Notes: The NVR is shown in solid black, with severity threshold 1 (dashed) immediately above and below, followed by severity threshold 2 (dotted line). The alteration magnitude is thus delimited in four grades of severity: slight, moderate, intermediate and severe.

Fig. 2. Severity grades of hydrologic alteration

Severe grades of alteration will cause appreciable changes in the functioning of the fluvial ecosystem; since the populations of living organisms that inhabit the affected stretches will have trouble recovering from these changes. In principle this situation should never be reached, since it may possibly be irreversible.

The other way to measure the severity of environmental problems caused by hydrologic regulation is to consider the frequency of the alteration. The first measure of frequency is made by counting for each parameter the number of years in which its value exceeds the NVR, obtaining a table which expresses the results in percentage terms. After that, we can evaluate the global impact on a given river by counting the parameters that fall outside the NVR for more than 50% of the years; this shows how many parameters are affected with great frequency and gives an overview not of the total impact on each river. Another general view of the situation can be obtained by calculating the mean values for each hydrological parameter on each river in the post-regulation situation and counting how many of them fall outside the NVR. This approach gives also a general idea, in a single number, of how many parameters are altered in the studied regime as a whole and to what extent.

In this study we use the results of the IHA parameters to analyze three main deviations from the NVR: how intensively the parameters are altered, how often they are altered and how many of them are altered each year. Thus the results can be ordered by the annual grade of alteration, which reflects how many parameters are modified each year and how severely, and in this way the number of parameters and the severity of the alteration are considered at the same time. The categories into which years are classified are: acceptable, moderate, medium, severe and unacceptable. These categories are assigned on the basis of the following requirements:

<u>Acceptable</u>: the regime management is considered to be acceptable in years without any parameter outside the NVR. This means that no alterations are being caused to the hydrologic regime.

<u>Moderate</u>: the regime management is considered to produce a moderate alteration in years when one or more parameters exceed the NVR but none passes severity threshold 1, i.e., no parameter exceeds a maximum value by more than 50% or is less than 50% of a minimum value. This means an alteration in the flow regime that is outside the normal variability range.

<u>Medium</u>: the intervention is considered to produce a medium effect in years when between 1% and 33% of the studied parameters pass severity threshold 1, i.e., exceed a maximum value of the NVR by more than 50% or are less than 50% of a minimum value. This means an alteration of a certain importance in the regime.

Severe: the effect is severe in years when between 34% and 67% of the studied parameters pass severity threshold 1, as defined in the preceding category. This severe alteration of the regime causes serious disruption to the river's hydrological and ecological processes.

Unacceptable: an unacceptable alteration of the natural regime is considered to take place in years when between 68% and 100% of the studied parameters exceed severity threshold 1. The modification of the regime is so serious that the functioning of the aquatic ecosystem may be irreversibly altered, preventing the development of life forms and biological processes in that waterbody.

A regime is also considered to be unacceptable when the magnitude of the alteration passes severity threshold 2, i.e., when any parameter that year has a value that is more than twice a maximum value of the NVR or less than 10% a minimum value of this range.

1.3. The indicators of hydrologic alteration basis for the estimation of the ecosystem economic value. To quantify the risk of alteration of a fluvial ecosystem process, as the hydrologic regime, and the transformation in monetary units to measure their economic valuation, are two works that can be framed in the strategies of estimating the value of the various services and benefits that ecosystems and biodiversity generate. In aquatic ecosystems that have a high degree of degradation in diverse parts of the world (Vörösmarty et al., 2010), the ecosystem economic valuation appears as a useful tool for the decision making in water ecosystems management, as well as for the sensitization and environmental awareness. In many contexts economic interventions, including the payments by services and markets, have existed for resources like water, and other natural resources which have been commercialized for a long time. Nevertheless, inefficiency and little effectiveness in the water administration and the wetland that maintains, have produced the subvaluation and the consequent low prices for the water. In this sense it has been reinforced the necessary efforts that have as objective to explore the potential of the water markets, using this research as a tool to reallocate the resource, in order to satisfy the needs of the ecosystems, as well as the traditional objective of improving the efficiency in the distribution of the stored water, for irrigation, hydroelectric and potable water supply. These strategies suppose the inclusion for the users, of tax and tariffs that burden not only the use, but also the deterioration of the ecosystem that have provided the resource.

In the last part of this work we have included some hypotheses and the necessary further development talk, to relate the degree of ecosystem alteration as consequence of human activities with the economic value motivated by this changes. This relations was linked with different types of economic value techniques, using the concept of Total Economic Value (Millennium Ecosystem Assessment, 2005). We examine the elements of economic value provided by rivers regime, and the most suitable técnics of economic valuation to apply, since monetary valuation can provide useful information about changes to human welfare, that will result from ecosystem management actions.

2. Results

The five analyzed rivers present different alterations. The three mountanous rivers (Gállego, Aragón and Segre) have hydroelectric plants on the considered stretches which manage their regulation and determine the type of alteration of their regimes, while the studied stretches of the two right-bank rivers have no hydroelectric plants and the water from their reservoirs is used for irrigation and regulation.

As a consequence, the number of affected parameters and the magnitude of the alterations differ between cases. The severity of the effects is also influenced by the size of the reservoir or reservoirs and by the installed capacity of the power plants in the case of hydroelectric regulation. The following table shows the results obtained after calculating the average and extreme NVR values of the pre-regulation regimes and the average values of the regulated regimes.

The results of this first analysis of the impact of regulation simply consider the frequency with which the values of the studied indices exceed the NVR (Table 3), without evaluating the magnitude of their deviation from the values considered to be normal. The river Guadalope shows a considerable number of indices which post-regulation values fall inside the NVR, while in contrast all the parameters of the studied stretches of the rivers Segre or Gállego fall outside this range in at least one year. In the case of the river Aragón, although the number of affected indices is smaller, one of these stands out significantly, namely that which measures the number of flow decreases, which has been altered every year after the regulation of the regime.

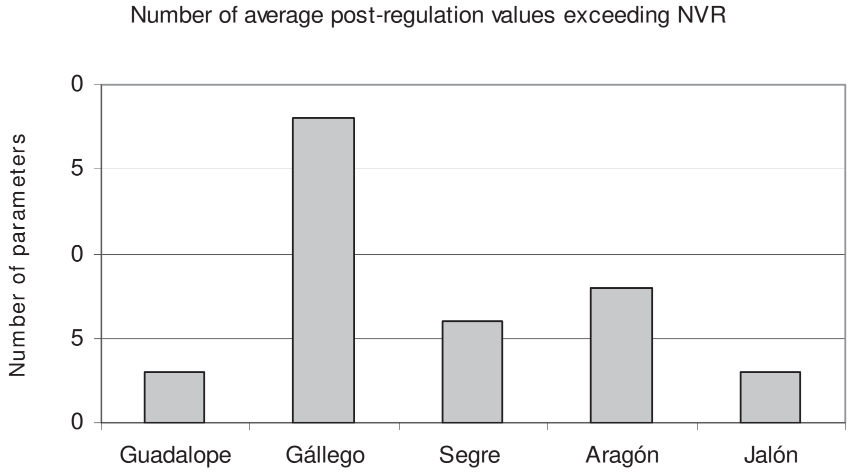
Table 3. Percentage of years (of the twenty after regulation) in which the obtained values of the 32 studied parameters are outside the NVR

	Aragón	Segre	Gállego	Guadalope	Jalón
Group 1					
October	15	10	5	0	25
November	65	35	40	55	20
December	55	10	45	40	0
January	35	35	50	5	20
February	75	25	60	70	10
March	60	25	70	75	0
April	60	25	65	20	5
May	80	35	80	75	5
June	80	35	80	55	30
July	0	15	65	15	55
August	0	35	60	0	70
September	0	20	55	0	15
Group 2					
Mean Max1D	50	45	70	95	25
Mean Min1D	25	35	80	0	25
Mean Max3D	40	40	65	95	10
Mean Min3D	20	40	80	0	30
Mean Max7D	55	50	65	90	10
Mean Min7D	10	40	90	0	40
Mean Max30D	55	50	70	80	20
Mean Min30D	5	40	80	0	50
Mean Max90D	65	45	70	80	15
Mean Min90D	5	35	85	0	45
Group 3					
Maximum day	50	20	50	45	60
Minimum day	35	35	45	65	0
Group 4					
High flow freq.	25	45	25	55	10
High flow durat.	20	60	5	65	5
Low flow freq.	40	50	40	75	15
Low flow durat.	35	35	5	30	20
Group 5					
No. flow increases	95	10	95	60	95
No. flow decreases	100	35	95	45	70
Mean of increases	45	30	60	90	20
Mean of decreases	35	70	60	85	15

Table 4 offers a more general appreciation in which a single number expresses the total alteration of the parameters over the studied period, thus facilitating comparisons between rivers. The second column shows the number of parameters which average post-regulation value is outside the NVR, and the third column shows how many of the 32 studied parameters exceed the NVR at least 50% of the years.

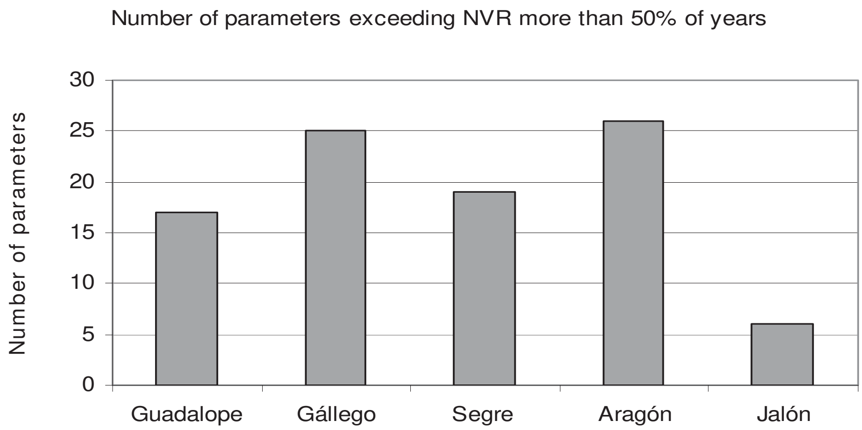
River, station, reservoir	Number of average post-regulation values exceeding NVR	Number of parameters exceeding NVR more than 50% of years
Guadalope (15) Santolea	3	17
Gállego (12) Bubal	18	25
Segre (104) Oliana	6	19
Aragón (101) Yesa	8	26
Jalón (9) La Tranquera	3	6

The Pyrenean Rivers Gállego and Aragón are those that most frequently present alterations (as can be seen in Table 4 and Figure 3), to the extent that of the 32 studied parameters, 25 and 26, respectively, are outside the NVR longer than within it. On the other hand, river Jalón, presents only six parameters outside the NVR in more than half of the studied years, and an average post-regulation value outside the NVR in only three cases. These results are displayed in graphic form in Figure 3.



Note: This figure shows the number of parameters which average post-regulation values are outside the NVR.

Fig. 3a. Frequency with which the parameters exceed the NVR



Note: This figure shows the number of post-regulation values that are outside the NVR more than 50% of the years.

Fig. 3b. Frequency with which the parameters exceed the NVR

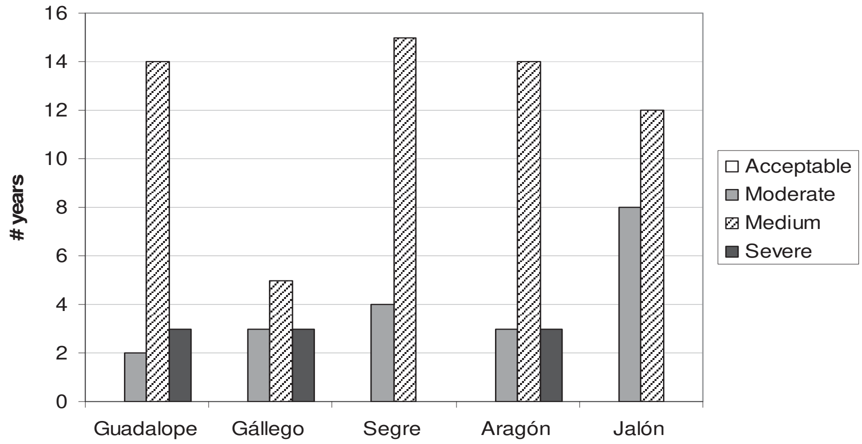
Regarding the results of the classification established to analyze the severity of the alterations, the most altered regime is again that of the river Gállego, while the least altered is that of the Jalón. The number of years corresponding to each of the established categories is shown in Table 5.

Table 5. Classification of alterations caused to studied regimes

River	Acceptable	Moderate	Medium	Severe	Unacceptable frequency	Unacceptable magnitude
Guadalope (15) Santolea	0	2	14	3	1	17 times
Gállego (12) Bubal	0	3	5	3	9	109 times
Segre (104) Oliana	0	4	15	0	1	21 times
Aragón (101) Yesa	0	3	14	3	0	15 times
Jalón (9) La Tranquera	0	8	12	0	0	5 times

Notes: Each year is categorized according to the percentage of parameters outside the NVR. A regime is considered unacceptable in a year where more than 68% of the parameters are outside this range, or when any parameter reaches severity threshold 2.

Figure 4 shows the same analysis of the 20-year classification in graphic form.



Notes: A regime is considered unacceptable in a year when any parameter reaches severity threshold 2.

Fig. 4. Graphic representation of alteration categories

3. Discussion

3.1. Hydrologic alteration. The results show that the interventions on the studied stretches have caused substantial alterations to the natural flow regimes of these rivers. The magnitude and the severity of these alterations vary from one case to another, and are more notable on the left-bank tributaries of River Ebro, where there is a considerable hydroelectric production, than on the right-bank tributaries, where the reservoirs are used for other purposes. Having noted this situation, the following discussion seeks to establish which parameters may indicate a more serious effect from the point of view of repercussions on ecosystem functioning and thus which rivers are more transformed, taking into account the findings of similar studies that have established relationships between regime alteration and environmental consequences. In this way it may be possible to predict the environmental effects that these changes will produce specifically on the studied stretches. Following this an attempt is made to define the steps towards an economic evaluation of the alterations, adapting these studies to the variables necessary for the application of existing natural resource economic evaluation methods, determining which of the variables used by these methods are available and which are lacking, and assessing the possibility of studying this issue in a way that is more in accordance with the particular case studied in this work.

The alterations that occur in regulated flow regimes, are measured by determining how far each parameter varies from its corresponding natural range, may be assessed in terms of the biological importance of each regime component for the populations that inhabit the rivers. For this purpose, the first interpretation of the results has consisted of observing the most outstanding variations in each of the five groups of hydrologic indices on each studied river and, on the basis of our knowledge of the relationships between flows and living populations, trying to predict the functional consequences that these specific alterations may cause on each stretch.

The following remarks on each river report the most notable results of this work, detailing the effects that the flow regime variations cause to the structure and the functioning of the river ecosystems, by comparison with the findings on other river stretches.

3.1.1. Aragón River modified by Yesa dam. This stretch of the river is situated in a mountainous area and its natural regime is influenced by snowmelt, with maximum flows in spring. Spring months present the greatest modifications in the altered regime after regulation, with mean flows in the months of May and June that are outside the NVR in 80% of the years (below NVR), as the mean values of the monthly indices show for the 20-year postregulation dataset. The timing of the maximum flow has shifted to the summer and is outside the NVR in 50% of the years in the regulated regime. The number of flow rises and falls has dropped dramatically, and these phenomena now occur half as often as in the natural regime. All the values of the indices that represent extreme high flows have decreased, especially the maximum annual maximum 90-day moving average, whose mean value in the intervened regime is outside the NVR. With regard to deviations from the natural magnitude values, the annual maximum flow value has unacceptable values for 3 years after regulation in which its values are so low that they pass severity threshold two.

Thus the regime has been strongly altered, affecting mainly the parameters that characterize the magnitude and the timing of extreme high flows. Daily flow oscillations have also been reduced, and there are now fewer flow rises and falls. This stretch can be considered to have lost its torrential character and the characteristic behavior of a high mountain river, and its floods have been laminated.

A number of environmental effects may arise as a consequence of the alterations observed on this river. The stabilization of the regime with a reduction in flood volumes may lead to less dispersion and lower efficiency in the colonization of new sites by riverside vegetation. With regard to fish, populations of exotic species may be favored and effects are also possible on the spawning of cyprinid species, which takes place in spring in several species; coinciding with the months in which the regime of this river has been most altered. Secondly, since the peak flows have shifted to the summer, damage may be caused to the shoots and sprouts of vegetation developed during the spring, and changes may also take place in the signals that mark the start of certain cycles in fish, since these are often adjusted to the timing of the maximum flows.

3.1.2. Jalón River modified by La Tranquera dam. On this river maximum flows decrease and minimum flows increase slightly; being the only parameters outside the NVR the 90-day minimum (45% of the years), and the mean value of this index in the period after regulation. The mean monthly values remain approximately equal to the values prior to regulation. The number of times the flow rises and falls is outside the NVR 90% and 70% of the years, respectively, and their mean values after regulation are also outside the natural range.

This is the least modified of all the studied rivers. The minimum flows increase slightly and there is not a year in which the river dries up completely, either before or after regulation, suggesting a slight advantage for the populations of living organisms after regulation since they do not have to resist a disruptive situation as intense or lasting as the magnitude of a drought, although this in most cases normally favours the more generalist groups, such as exotic fish species, and not so much the more specialized species. In addition to this phenomenon a reduction in flow variations is present, affecting both rises and falls. It has been reported that this standardization of flow values in the regulated regime also favors colonising species that are not adapted like the native species to more fluctuating regimes (Meffe, 1984). The functions performed by flood flows may be altered since these are smaller in magnitude, e.g., flooding of banks, renovation of riverside vegetation, maintenance of soil humidity, and cleaning the substrate of fines.

3.1.3. Gállego, modified by Bubal dam. This is the most modified river of all the studied ones. It should be taken into account that the site where the flow data was recorded is affected by two large hydroelectric production dams. The repercussion on flows is particularly serious and affects both their frequency and their magnitude: all the indices that represent high and low flow magnitude are outside the NVR. The mean values of all the months decrease, especially the spring and summer months, whose values are outside the NVR between 70% and 90% of the years, and the average of all the values is also outside the NVR. Of particular importance is the impact produced on this river in terms of the magnitude of the deviation caused to the values of its indices compared with the values considered to be natural; it can be seen in Table 5 that the regime is classified as unacceptable due to the magnitude of the effect on 109 occasions. This result is repeated in the values of the minimum annual 7-, 30- and 90-day moving averages, which represent low flows during prolonged periods of time. In the particular case of the 90-day moving average the average values on the river go from 12 m^3/s prior to regulation to values of less than 1 m^3/s after regulation, and bearing in mind that this situation is prolonged in time, the stress situation to which the biological populations are subjected is very considerable. The reduction in mean flows in the months of April, May, June and July is also considerable, and unacceptably low values have been found in these months on more than 9 occasions. Moreover, the timing of minimum flows has also shifted from the end of September to May.

The reduction in flows is probably the disruption that has the most serious consequences on the stability of aquatic populations, besides being the most documented. The problem worsens if these reductions are prolonged in time and take place on different dates to when they occur naturally, since the affected populations are unable to develop strategies to respond to these critical situations. Such low flows reduce dramatically the habitat availability in the affected stretches and the connectivity between reaches cutting the way to migration or other strategies developed by aquatic organisms periodically subjected to short drought periods. The effect caused to riverside vegetation is clear, since it will be deprived of sufficient amounts of water, causing a decline in vegetative growth, morphological changes and the desertification of areas where water flows are insufficient.

3.1.4. Guadalope modified by Santolea dam. On this river there is a reduction in the volume of flowing water, both in the yearly maximum and minimum extremes and in the monthly averages. The regulation of high flows is especially irregular, even though the mean values of the indices that characterize them after regulation are within the NVR. According to the data, the individual values of these indices have decreased in most years, but in three years their values have increased, thus balancing out the average. However, if analyzed individually on a year by year basis, this is the group of values and the river for which the high flow indices are outside the NVR on the greatest number of occasions (up to 95% of the years).

The timing of the minimum flow shifted from spring to the month of July. This regime, which in natural conditions may be considered a mixed rain/snow-influenced regime, has been thus transformed into a regime where the greatest flows are found in summer, quite the reverse of the natural situation. It is also seen that the average duration of flow rises and falls has decreased, and although the difference is small in terms of units, the new figures are outside the NVR. The values for which the regime is considered to be unacceptable in terms of magnitude are those that refer to the decrease in high water flows, which in several years are far out from the NVR.

Likely, the geomorphological and ecological functions performed by the different levels of high water flows characteristic of most rivers will be modified and even lost (Poff et al., 1997; King, 2004), decreasing the diversity of riverside vegetation species and the extent of their favorable habitats, as well as the transportation of fine sediments. Other phenomena that will be affected by the reduction in the highest flows are those that maintain the diversity of the fluvial microhabitat and supply the organic matter that serves as food for a variety of benthic animals. The functions associated with the highest flows would also be lost, such as sanitary effects on old trees, replacing them or removing dead branches and allowing the colonization of new spaces by new plants.

3.1.5. Segre modified by Oliana dam. The most notable feature of the modified regime is the increase in values compared with the natural regime; the increase in minimum flows means that three of the indices have averages outside the NVR after regulation. One explanation for this unusual situation would be that the river is receiving transfers from other nearby reservoirs to increase its electrical production capacity, while another would be to attribute it to changes in land use and urbanization of the headwater areas of this river and its tributaries (Batalla et al., 2004). Other alterations observed include an increase in the frequency and the duration of high and low water flows and in the duration of flow decreases, which now last longer.

The increase in flow on this river, and especially in the maximum values, may give rise to changes in the geomorphology of the channel, although such processes also involve other parameters for which data is not available, such as the sediment load. The alterations that produce the greatest repercussions on biological populations are the increase in the frequency and duration of extreme flows. In the case of droughts, this phenomenon produces a stress situation in these populations which if prolonged may give rise to irreversible situations, modifying the values of their diversity and complexity. At the other extreme, the prolonged duration and greater frequency of high water flows leads, for instance, to the loss of riverside vegetation due to the rotting of roots or the loss of the larvae and juveniles of species that spawn in shallow areas.

Within the abundant research that has been performed on the relationships that exist between streamflow and populations of living organisms, their dynamics, and the river's dynamics, it is interesting to consider that which describes the repercussions of certain flow modifications on specific aspects of the physical or biological environment, which may therefore be of use when trying to establish severity categories or to evaluate from an environmental viewpoint the consequences of modifications in each index. This could be used in future economic models which seek to internalize environmental impacts and establish establish a regime of taxes and/or sanctions, with regard to the weighting of each regime component to reflect the severity of their alteration in the variable that represents the disruption caused to the physical environment and quantifies the externality in economic terms. Experience is available above all on the consequences of the flow changes that occur most often in regulated regimes (Yount and Niemi, 1990; Poff et al., 1997; King et al., 2000; Cable, 2003; Lytle and Poff, 2004), which tend to coincide mainly with the effects caused by:

- Decreases in low water flows.
- Lamination of floods.
- Increases in frequency of flow value changes.
- Modifications in timing of extreme flows.
- Modifications in duration of extreme flows.

Table 6 lists a number specific studies on the environmental effects of modifications similar to those produced on the studied stretches in the Ebro basin.

Table 6. List of hydrological alterations and their biological consequences, indicating the stretches in the present work where these have been found

Type of alteration	Biological effects	Reference	Rivers in present work where this occurs
Reduction in low flows	Effects on fish and riverside vegetation	Cooper et al. (1999) Stromberg (2001)	Gállego

Table 6 (cont.). List of hydrological alterations and their biological consequences, indicating the stretches in the present work where these have been found

Reduction in flood magnitude	Effects on fish	Cattaneo et al. (2002) Ortlepp and Mürle (2003)	Aragón, Gállego
Increase in frequencies	Effects on fish and macroinvertebrates	Robison et al. (2003) Ortlepp and Mürle (2003)	Segre
Alteration of timing	Effects on fish and riverside vegetation	Elliot et al. (1997) Bowen et al. (2003) Stromberg et al. (2007)	Aragón, Gállego, Guadalope

If the ultimate aim is to achieve an economic valuation of the alteration so that environmental costs are taken into account in the productive system which exploits that stretch of the river, it is necessary to analyze the environmental consequences that are produced by this alteration, and this will depend on the number of parameters that are altered. The simplest criterion is to consider that all the parameters analyzed have identical consequences, and in this way assume that the modification of any parameter will produce similar effects than the modification of any other, as a result of which the valuation of the alteration produced by the intervention will only provide a measure of the number of parameters modified, their frequency, and the distance between the current values and the permitted values. However, it is very tempting to classify the alterations in order of their importance for the functioning of the ecosystem. This will allow us to know if the deviation of one parameter from the natural values has the same ecological consequences as that of any other, or if the alteration of one hydrological value in the functioning of these systems produces more harmful effects than the alteration of another. To establish this evaluation it would be necessary to be provided with a field of experimentation which in many cases is difficult to achieve; the ideal situation would be to have a regulated river where controlled releases of water could be performed, varying the magnitude and the frequency of the hydrological parameters, and at the same time recording data on biological consequences such as the number of species, diversity, density, biomass, production and stress.

One possible experiment would be to evaluate two different changes to the same type of parameter on the same stretch and in the same conditions, e.g., short, frequent reductions in flow versus one single long, drastic reduction, which would allow a study of the effects of the frequency of change in flows, while at the same time measuring its effects on the populations of living organisms that inhabit that stretch.

In view of the impossibility of having such a precise field of experimentation, many studies have been carried out comparing the biological response of a regulated river before and after the construction of the regulating infrastructure, or comparing a regulated river with a nearby unregulated river of similar characteristics. These experiences normally yield results on the effects that are produced by a variation in one single hydrological parameter and do not allow comparisons between the effects of various parameters on biological communities on the same stretch of river. Studies of this type have been approached in five different ways:

- Analyzing stretches that are to be regulated before and after the intervention (Muñoz and Prat, 1996).
- Regulated rivers on which management of the flow for scientific purposes is allowed (Jhonson, 1995; Robison et al., 2003; Ortlepp and Mürle, 2003).
- Regulated rivers on which a regime restoration program has been established (Jowett and Biggs, 2004).
- Analysis of riparian vegetation using aerial photos of stretches and their corresponding flow data (Shafroth et al., 2002).
- Comparison of altered stretches with stretches of nearby rivers of similar characteristics (Bowen et al., 1998; Merrit and Cooper, 2000).

Weighting the environmental damage that is caused by each possible intervention in a regime can help to evaluate its economic cost, as is proposed in the present work, but may also help to improve the regime management by recommending the incorporation of a monitoring program to assess the severity of the actions when programing releases. Furthermore, these considerations should be taken into account in the design of the infrastructure and the way its production is organized, in order to reorient any parameter that is highly determining in the functioning of the ecosystem towards more natural values. Highly positive environmental recommendations do not necessarily need to involve costly impacts on electricity production, when the regulation is of hydroelectric origin, or on the management of reservoirs that are used for other purposes.

3.2. Economic evaluation of the effects of hydrologic alteration based on the economics of valuing ecosystem services. The evaluation of natural resources is intrinsically highly complex and difficult matter. This case is further complicated since we intend not to evaluate the resource itself but the economic value of the compensations that the users should pay for the damage caused to the system. The ultimate aim of these compensations would be the improvement of management practices in these businesses.

The analysis of economic values also suggests that there may be the opportunity to recover some of the costs of the rivers' alteration from those who directly benefit from them. The main costs of establishing natural flows restoration are typically those related to offset the benefits generated by existing water infraestructure and uses, these are typically measured in financial terms, for example the net benefits of hydropower or farming. The price of the goods and services involved is easily observed in the marketplace. The benefits of environmental restoration, however, are often difficult to quantify. In many cases, they do not pass through markets and, thus, have no observable market price or quantity. As we introduced previously if we consider the type of the ecosystem service that we are trying to evaluate, we would find an useful valuation method that normally are used to valuate this particular ecosystem services. Since a natural flow regime provides indirect benefits in the ecosystem and other components of its surroundings, taking into account the most common categorization of the available techniques used to value ecosystem services, we can catalogue this service like a Service of Regulation (Pascual, 2010). Regulation services have been mainly valued through avoided cost, replacement and restoration costs, or contingent valuation (Martín-López et al., 2009).

Although less frequently, also the Market Prices Method can sometimes be applicable to regulation services. This can be debatable but in the majority of the cases it is easier to apply. In the case of the flow regulation produced by the hydroelectric production, the price of the energy or the other service associated to the fluvial ecosystem, as the fishing resource, can be used. The first method would consider the benefits obtained by the electrical sector as a result of the water use in hydroelectric power plants, considering that the deterioration of the environmental status must be charged in relation to the benefits of the energy production obtained in these plants. This approach has been used in Spain by the Management Water Agency in Catalonia (ACA), when an attemption of implementing an environmental flow proposal in a series of rivers, strongly regulated by hydroelectrical production was tried. These previous proposals were included in the package of measures suggested in the Management River Basins Plan in application of the WFD (Water Frame Derective). In this work (Munne et al., 2009), it has been considered that only 25% of the power instalations would have problems in adapting to the proposal of environmental flows. Here, the possibility to compensate the promoter by the dismissed profit is contemplated. The quantity of this indemnity would be of 75 mln €, this would be a maximum cost of 23€ per inhabitant and year during 52 years. From a goverment perspective, providing funds should be contrasted with the altertative of simply mandating change. In some countries, the last approach may be more feasible, but in many countries any efforts to "take" existing property rights, for example Spain, are likely to be resisted. Although the approach is totally in opposition to which is being treated in this article, by a long and old legal concession of the use of water to the electrical sector in this zone, but the technique would be similar to which we tried to develop hereinto. The number of examples will increase as the River Basin Plans of the European rivers, will be redacted in application of the WFD, with their own action programs to improve the ecological state, in addition, because these programs must go accompanied of its economic budgets.

In application of market methods we have proposed two models for the river alteration situations studied. The first calculates the economic compensations proportionally to the monetary benefits obtained by the business that exploits the system (e.g., the electricity company) and the severity of the overall damage caused, irrespective of the environmental parameters that are affected. In the second method the affected environment is studied and its natural assets are evaluated, considering that the compensations must be determined by the measurable modifications that are caused to one or many of these natural components.

Let us take the river Gállego, for example. The stretch studied in this work is subjected to the regulation produced by three hydroelectric plants upstream: Biescas I and Biescas II on Bubal reservoir and Lanuza on Lanuza reservoir, each of which has several production units. There may be other electricity generating facilities on the river but these are not taken into account since they are of a comparatively much smaller installed capacity. According to data published by the National Energy Commission (CNE) in 2001 the total production of these groups was of 241,712 MWh, and considering that the average end price paid that year to electricity producers in Spain was 3.859 c€/kWh, they sold electricity for a total of 9,327,666 €. If a charge is levied on this system for the negative environmental effects that are being produced, according to the philosophy of the first method presented above this value must be proportional either to the total benefits or the number of kW produced. The proposed formulation is similar to that applied for the calculation of discharge royalties:

$C = K \times N \times P$,

where C is the total amount to be paid (in euros); K is a factor that depends on the severity of the alterations detected (in euros); N is the number of kW produced in the year; and P is the number of parameters that are outside the NVR.

A similar estimation is being used following a proposal by the Spanish Geological and Mining Institute (IGME) to value and include the aquifer affection by fires or contamination, as economic damages.

The impact is calculated according to four variables:

$I = T \times P \times U \times A$,

where T is the type of aquifer, P is the position of the aquifer in the river basin, U is the destination or water use and A is the affected area. The finally value is calculated taking the I estimation impact, multiplied by the water lost amount and by a reference price of water (IGME, 2007).

Within the second group of methods the economic evaluation will depend on a particular component of the environment that may be evaluated. One of the natural resources that is known, assessable, appreciated, and to which a monetary value can easily be attached is that of fisheries. To continue with the same stretch of the river Gállego, the Environment Department of the Regional Government of Aragon has established a fishery reserve downstream of the Bubal dam, known as Olivan reserve, with a length of 6.5 km and which predominant species is the common trout (*Salmo trutta L.*). As this river stretch has a fishable production that may be determined, the evaluation will start with the performance of a study of the population, assessing its potential (biomass extractable that year which would be replaced by the annual growth of the population) and comparing this with the hypothetical situation if the stretch were not altered (data from the pre-regulation period or nearby similar stretches). These calculations give the result of the alteration in kilograms of biomass per meter length or per stretch, which must then be transformed into monetary units. As the recovery of the population will depend on how many parameters are altered, the amount to be claimed from the company exploiting the resource must be proportional in value to the number of parameters and the biomass which is not fishable as a consequence of the disruption.

Other group of methods applicable to the valuation of regulating services produced by the ecosystems is the Mitigation or Restoration Cost method, which refers to the cost of mitigating the effects caused by to the loss of ecosystem services or the cost of getting those services restored. An example, in which a very direct application of this method is used is the restoration of the River Urumea in the north of Spain, where also the main problems is flow regulation. This study is being carried out thanks to the economic aportation of a european project called Bidur (POCTEFA, 2007). The main objective of this project is to recover salmon populations in this river, in which their migratory trips have been modified by the succession of obstacles, small dams, that has settled for many years in their channel to hidroelectricity production. The project is trying to make permeable the river, doing possible the ascent of the salmon to the spawing areas, for that purpose diverse works are being undertaken, not only at fish scales but also the demolition of the obstacles. In an economic estimation on the cost of permeabilization of rivers sections made by the Provincial Council of Gipuzkoa, which include the works in the Urumea rivers, have calculated that the 51 proposed solutions add a total investment of 3,574,068€. This means an average budget of 70,080€ for every actions, although with significant differences (Tames, 2007).

The economic value proposal in this work implies that the costs of these works must be assumed by the producers of the electrical energy, partly by the regulation and modification of the flow regime which they are imposing in the river reaches of the affected rivers, the valuation of the total cost of the restoration could be distributed proportionally between the number of power plants and weigh according to the magnitude of the alteration produced in the natural flow regime.

The Stated Preference methods are other group of methodologies in the evaluation of natural resources appling to regulating services, this techniques can be used to estimate both use and non-use values of ecosystems and/or when no surrogate market exists from which the value of ecosystems can be deduced. The main technique of the stated preference methods is the contingent valuation method and its variant called the travel cost method. The advantage of these methods is that they evaluate the environment as a whole, not just fishery resources evaluated by fishermen, but all the fluvial system with all of its environmental values (all the populations of living organisms, the riverside environment and the landscape and cultural values, etc.).

Finally, another way of addressing the problem is to make a cost-profit analysis. In this case, society must value both the utility of a consumer good such as electricity and the presence of fish populations in its rivers, trying to maximize the utility function of the system that is represented. To establish this function the components of the system must be considered. These may include, among others: the production of electricity, the production of trout, the stock of trout, and the dependence of these productions on the streamflow. The equation must consider the way in which one particular regime or another influences the production of electricity (the cost of the opportunity of maintaining a healthier trout population for example), in order to establish the function that determines the relationship between the type of regime and a production value or biological value of the trout population (e.g., its possibility). The cost-profit analysis will take into account all of these parameters and will use the latter relationship to generate the values of the main terms considered in the analysis. The only reference found to the application of this type of analysis in a conflict caused by the modification of the natural status of a river refers to the case of a river in Sweden (Hakansson et al., 2004). The river was regulated by a hydroelectric power plant, where a pilot study was carried out to determine the parameters that established the value to citizens of the preservation of wild salmon.

Conclusions

The authors believe that this issue comes down to the key question of quantifying the loss that is suffered, for instance in electricity production, by taking the regime to a status that is more natural or more similar to the natural status. It is quite likely that the result would be surprising and that the costs involved would be very low, since the question is not to produce less or to turbine less water but to do it in a different, more sustainable way. The successes achieved on some rivers where the effects of regulation on biological populations were taken into account have been highly notable with only very slight variations in the management or the turbining regime of power plants (Jowett et al., 2004). These good results support the fact that negotiation between the affected stakeholders, such as representatives of the productive sector and citizens that appreciate natural values, offers a tool which allows the improvement of the status of our rivers and eliminates the need for other types of actions that are much more difficult to implement.

The application of this methodology based on the NVR approach showed that it is possible to assess, quantify and classify the degree of hydrologic alteration for a given fluvial stretch. The analysis allowed to distiguise different types and degrees of flow regime alteration in magnitude, timing and frequency.

Further research is needed to identify and measure the specific effects of each alteration (32 parameters) on the quality elements (fishes, macroinvertebrates, algae and riparian vegetation) comprising the ecologic status of surface water bodies. For this purpose open air experiments should be carried if possible.

The assessment of the level of hydrologic alteration can help to evaluate its economic cost but may also help to improve management procedures (flow releases schemes) and to recommend the implementation of a monitoring program to assess the impacts of individual flow releases.

Considering the different methods that exist to value ecosystems services, in the majority of them it is necessary to have a quantitative base that it allows a more exact calculation, than can be used to relate the economic value with environmental parameters referring of the state of the ecosystems. The quantification of the hydrologic alteration of river stretches is a useful output for management, restoration activities and economic evaluation. Once determined the degree of alteration for a given ecosystem, research should focus on the economic evaluation of its effects in order to allow the establishment of a compensation program. Most analyzed methods of economic evaluation are based on the evaluation of a specific element in the ecosystem with relevant economic impact. Further research is needed to evaluate the ecosystem as a whole in the framework of the Total Economic Value (TEV) of the ecosystem approach. The basic philosophy underlying the present work is that society can assign values to ecosystem services and biodiversity only to the extent that these fulfill needs or confer satisfaction to humans either directly or indirectly.

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