

A comparative analysis of methods for establishing environmental flows in a Mediterranean watershed: suggestions for management

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ABSTRACT

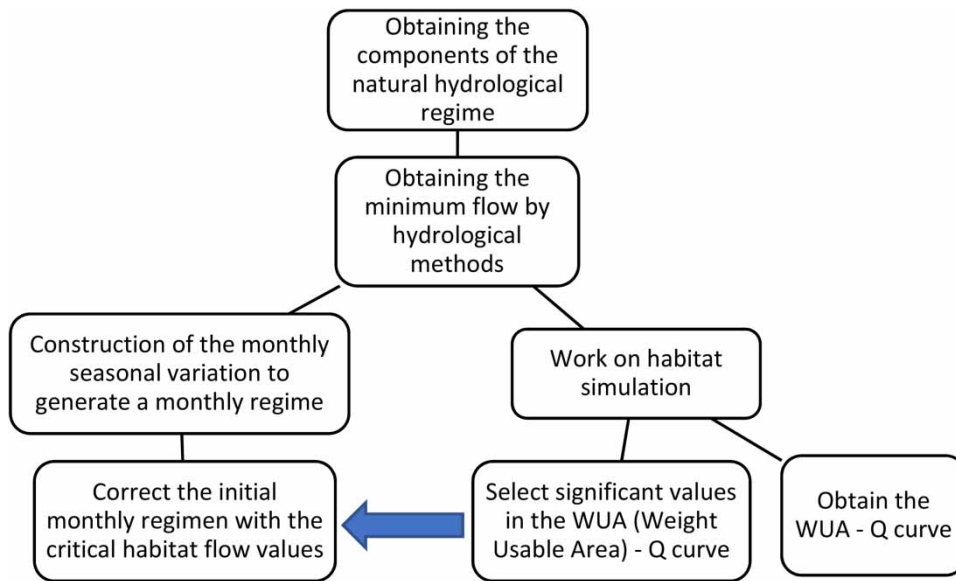
In Spain, the largest inter-basin transfer is between the Tagus and Segura Basins. This transfer affects the regimes of the Mundo River, a tributary, and the Segura River. In this study, we examine two methodologies for the calculation of environmental flow regimes for the stretches affected by this alteration. When several methodologies are used to determine environmental flows, difficulty arises in deciding which values to propose to restore the river system hydrologically. This work tries to overcome this problem because we present a proposal to make them complementary. As a method for establishing the validity of minimum flow results, a simulation has been carried out on the river section, which has made it possible to evaluate the habitat created and the possibility of fauna movement. The results obtained by the *habitat simulation method* exceeded those obtained by *hydrological methods* in terms of habitat creation and hydraulic conditions for connectivity. These same tests have been used to assess the minimum official proposal made by the water administration.

Key words: environmental flow, habitat simulation, Mediterranean rivers, water management

HIGHLIGHTS

- A procedure has been established that allows different results of ecological minimum flow values to be used in a complementary way to improve fish habitat.
- When results obtained by several methodologies are used in a complementary way, a more robust ecological flow regime proposal can be made.
- The method used can be applied together with other restoration measures in river stretches with strong morphological alterations.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Recent advances in ecosystem restoration have shown the importance of the basic physical processes governing ecosystems and the need for these processes to resemble natural values for the conservation of the conditions of natural systems (Palmer *et al.* 2005). In flowing water, the most important parameter in terms of variability and seasonal dynamics of physical events is the flow regime (Olden & Poff 2003; Poff *et al.* 2007). When the aim is to preserve or maintain the river in 'good' ecological status, the natural regime can be used as a reference to calculate the components of the environmental regime (Baeza & García de Jalón 2005). Therefore, when an action to improve the ecological status of a river by altering its flow regime is undertaken is first necessary to understand the natural regime of hydrologic variation in the area of study.

The causes that can produce this alteration are varied, but the most frequent are the presence of large regulating dams and the water transfer from one river basin to another.

The ecological impacts of these major obstacles and their management in the aquatic ecosystem can be classified into two groups: those related to hydromorphological changes and those related to the movement of fauna (Burke *et al.* 2009; García *et al.* 2011). The former includes changes in river morphology, disruption of sediment dynamics, and changes in water chemistry and temperature. The main environmental effect of these installations is a change in the flow regime.

Regarding the effects on wildlife, we can consider the following (Benejam *et al.* 2014; Boavida *et al.* 2015): barriers to migration and dispersal of protected species, injury and killing of individual animals, and changes in river habitats. A change in flow regime can reduce or degrade the extent of aquatic habitat, as well as its connectivity with riparian habitats. Fluctuations in flow velocity, depth, and the area of the channel that is wetted by water have a significant impact on fish habitat, both in terms of availability and quality. Environmental flows maintain river ecosystems downstream of these infrastructures by reducing the gap between the altered and natural flow regimes, improving habitat downstream of dams, and facilitating wildlife movement (Kuriqi *et al.* 2019; Owusu *et al.* 2020).

Environmental flows are also used to minimise the environmental effects of diversions and are usually applied to the donor river and sometimes also to the recipient river, the experience accumulated for determining environmental flows is extensive, and there are several methods to estimate the flow values that allow the preservation of the functionality of the fluvial ecosystem (Linnansaari *et al.* 2013; Pastor *et al.* 2014; Ramos *et al.* 2018; Mezger *et al.* 2020; Tickner *et al.* 2020). The discussion about which method is best to apply to certain altered rivers is conditional on several variables. The main one is what objectives are to be achieved with the regime proposal, but other factors such as the availability of source data are also important.

In this work, we start with the estimation of the minimum flow using several methodologies. Without going into depth about which solution is best for the problems that these rivers present, the objective is to seek complementarity between the results so that the final proposal is built based on several approaches with the purpose of obtaining the best in terms of improving the ecological status of the river section where it is implemented. For this, we are using a particularly critical hydrological point in Spain, where a hydraulic infrastructure has recently been built. This infrastructure completes an existing transfer that may have consequences for the water flow of the two affected rivers, the Mundo and Segura Rivers, located in the southeast of Spain.

Inter-basin transfers between different rivers cause alterations in the contributing river that manifest in changes to the flow regime as well as changes to the receiving river (Rollason *et al.* 2021). The flow regime of the Mundo River, a main tributary of the Segura River in the province of Albacete (Spain) (Figure 1), is highly altered by the Tajo-Segura inter-basin transfer. This transfer carries water from the Tajo Watershed in central Spain to the Segura Watershed in the southeast, where it enters the Mundo River through the Talave Reservoir (OPH-C.H. TAJO 2021).

A new infrastructure that will be in operation soon may be an appropriate place to test an improved hydrological restoration measure. The new infrastructure is projected to increase the disturbance on the hydrologic system of the receiving watershed. A tunnel will connect the Talave Reservoir, which receives the water from the Tajo, with the Cenajo Reservoir on the Segura River. The purpose of the tunnel is to improve the capacity for flow regulation by using the Cenajo Reservoir, with a capacity of 437 Hm³, in comparison with the Talave Reservoir, which can hold 35 Hm³ (Figure 1). This new transfer will have two impacts: it will reduce the amount of water in the Mundo River and increase the flow in the Segura River, the receptor of the transferred water. For these reasons, a series of hydrological restoration measures are necessary to reduce the impact caused by the flow alteration.

The methods that have been applied for flow estimation in the Segura Watershed are of the hydrologic type; one is known in Spain as the Maintenance Base Flow (QBM; Palau & Alcázar 2012). The QBM method is widely used in Spain and is based on a series of mobile means of different interval lengths that are calculated from natural daily discharge records. In

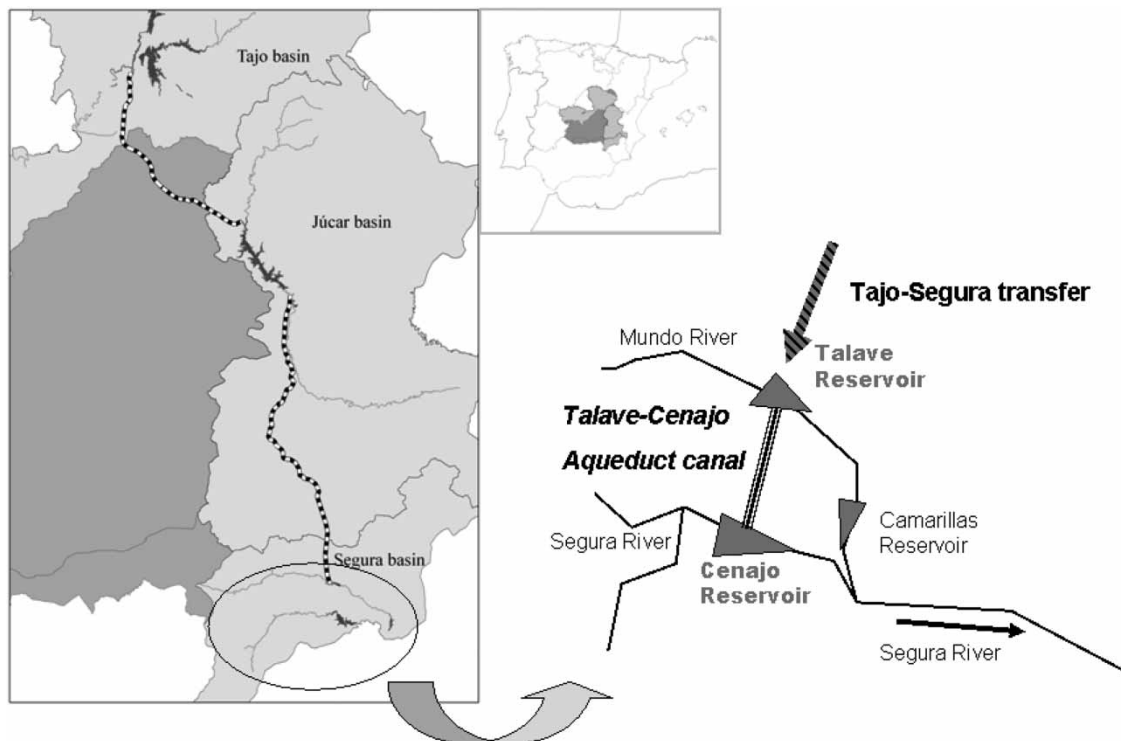


Figure 1 | Location of the Tajo-Segura transfer in Spain and the new channel between the Talave and Cenajo Reservoirs. The reaches where topographic surveying and discharge measurements were taken are downstream of the two reservoirs, named DTR (Downstream of the Talave Reservoir) in the Mundo River and DCR (Downstream of the Cenajo Reservoir) in the Segura River.

the official Watershed Hydrology Plan, this value calculated by the QBM method has not been contrasted with any environmental objective, such as the amount of habitat created or the improvement of the ecological status in the river section. In addition, the monthly modulation constructed from that minimum flow gives very low values for the rest of the months (OPH-C.H. Segura 2015). This flow regime is not based on any scientific evidence and it is considered insufficient for meeting environmental conservation goals (Sánchez Navarro & Martínez Fernández 2007).

This treatment is given special importance because it has direct implications for water management since the implementation of the European Water Framework Directive (WFD 2000). The WFD introduced the concept of hydromorphological indicators among the variables used to evaluate the ecological status of water bodies, given that rivers with similar flow regimes may have similar processes (Arthington *et al.* 2006). The WFD defines the category 'highly modified water bodies', meaning surface waters that have experienced a substantial change in their nature. These alterations may be in the hydrologic regime. The Segura Basin hydrological plan classifies these two water bodies as highly modified water bodies since they are located under reservoirs and their hydrological regimes are highly modified (Richter *et al.* 1997). The proposal and implementation of an environmental flow regime can contribute in a very relevant way to achieving the environmental objectives in these rivers' sections. In addition, a regime close to the natural flow can contribute to improving other alterations, such as morphological ones.

This study aims to offer a proposal to design a more complete flow regime so that we can compare it with the environmental regime included in the current basin hydrological plan. It also serves to extend it to other river sections since it includes the most relevant of several methodologies and proposes a method for these methodologies to be complementary. This study seeks not only to compare different methods that estimate minimum and maximum flows to derive an annual flow regime but also to select and give advice about the strategy so that some values obtained with one method are modified with those of the other methods. In particular, the goal is to obtain better environmental results that have been proposed for improving the ecological status of rivers in general and those of the Mundo and Segura Rivers, as specified by the WFD (Ramos *et al.* 2018).

As another contribution to this work, we used several checks to compare the hydraulic conditions produced by minimum environmental flows. We derived these conditions from calculations made by the Spanish hydraulic administration and compared them to those obtained by the values of our hydraulic simulation. The ultimate goal is to validate the different results with a test that promotes more natural physical conditions and proposes environmental flows to re-establish habitat conditions of key species, giving special consideration to the monthly flow pattern in terms of quantity, duration, and frequency of characteristic volume in order to improve the physical and habitability conditions of the river sections being restored.

As a principal contribution, the main objective is to obtain a seasonal regime that is based on habitat conservation, as opposed to the simpler proposals that provide a single minimum flow value or that where monthly changes are made by simple hydrological methods without a determined objective (Schulte & Harshbarger 1997).

1.1. Study area

The reaches incorporated into this research are the midreaches located downstream of the Talave and Cenajo Reservoirs on the Mundo and Segura Rivers, respectively (Figure 1).

The reference gauge station data was taken from two stations in the headwaters, an area with no influence of regulation by dams. Reaches will be abbreviated in the text as:

DTR: Downstream of the Talave Reservoir.

DCR: Downstream of the Cenajo Reservoir.

The gauge station reaches the following locations:

UTR: Upstream of the Talave Reservoir.

UCR: Upstream of the Cenajo Reservoir.

The DTR reaches on the Mundo River are located below the Talave Dam; the length of the reach is 180 m and its width varies between 21 and 16 m.

The DCR reach in the Segura River is straight and located below the Cenajo Dam; we performed the analysis on an area 105 m in length and 17 m in width.

The flow regime in the headwaters of the Segura River during most of the year follows the Mediterranean precipitation regime, with high flows in the autumn and low flows during the summer. This river flows through one of the areas with

the lowest mean annual precipitation in the Iberian Peninsula (less than 300 mm/year on average) and a very irregular precipitation inter-annual regime; as a result, this river experiences many years of drought and, on occasion, large floods. Those are two of the main characteristics of its particular hydrologic cycle.

The fish community is made up of *Salmo trutta* L (Brown trout), *Luciobarbus sclateri* (European barbel), *Pseudochondrostoma polylepis* (Iberian nase), *Gobio gobio* (Gudgeon), *Micropterus salmoides* (Largemouth bass), and *Lepomis gibbosus* (Sunfish). The species *P. polylepis* and *G. gobio* are native to Spain but introduced into the Segura Watershed, while *M. salmoides* and *L. gibbosus* are not native Spanish fishes. Given that the only native species located in the stretches is *L. sclateri*, the preference curves of this species (Martínez-Capel & García de Jalon 1999; Martínez-Capel *et al.* 2009) were used to obtain the results of the minimum flow in the habitat simulation, for the estimation of the environmental flow regime.

2. METHODS

Establishing an ecological flow regime for the two reaches of this study requires three steps: (1) calculation of the minimum ecological flow: this is a computation of the lowest monthly value, below which the structure and functioning of the ecosystem are compromised. (2) The monthly changes in flow, which will give a pattern for watershed management in terms of programming reservoir releases to resemble the natural regime. Finally, (3) the norms to follow in considering other flow regime components critical to the biological communities, such as magnitude, duration, frequency, time of year, and pattern of changes in discharge.

The two most commonly used methods for defining environmental flows are the hydrological and habitat simulation methods (Paredes-Arquiola *et al.* 2011). These techniques can produce significantly different results, especially in rivers with some singularity in terms of summer regime. For this reason, the proposal of this work is to correct the results of the monthly regimen obtained by hydrological methods using the results obtained in the habitat simulation.

The beginning of our work consisted of obtaining the components of the hydrological regime. To establish the regime components, flow data over a long time period is required to determine hydrologic indicators (Olden *et al.* 2012). We used two groups of data to obtain baseline natural daily flow values for the studied basins: (1) Data from gauge stations located upstream of the inter-basin transfer and reservoirs and (2) Monthly natural flow series reconstruction (CEDEX-SIMPA 2012) for reaches downstream of reservoirs and near study reaches.

Daily flow records with few significant changes were obtained from the Lietor gauge station (EA-050); we designated this point as the Mundo River's upstream Talave UTR records point and the Fuensanta gauge station (EA-001) as the Segura River's upstream Cenajo UCR records point (Figure 1 and Table 1).

Once a regime similar to the natural one has been obtained that serves as the basis for hydrological calculations, the strategy to obtain an improved regime that considers the production of habitat would consist of the following steps:

- Obtaining the minimum flow by hydrological methods.
- Construction of the monthly seasonal variation to generate a monthly regime.
- Work on habitat simulation is required to obtain the WUA (Weight Usable Area)-Q curve.
- Select significant values in the WUA-Q curve that are considered critical in system operation.
- Correct the initial monthly regimen with the critical flow values that provide a sufficient habitat for fauna.

2.1. Calculation of minimum flow

The minimum ecological flow was calculated using the hydrologic method and hydraulic simulation. The hydrologic minimum flow value is based on statistical methods for calculating moving averages and consists of obtaining a series of moving averages of different interval lengths (beginning with an interval of 2 days and going up to 110 days). In this study, we made the final choice of minimum flow by applying two criteria: the Maintenance Base Flow (QBM; Palau & Alcázar 2012), used by the Spanish Official Water Administration and the method based on the work of Baeza & García de Jalón (1997). This last method chooses the minimum flow by analysing the slope of the curve (flow-moving average interval size). We took the minimum flow values from the point where there is a change in slope, indicative of the beginning of stabilisation.

2.2. Ecological flow regime

Once the minimum ecological flow had been determined, the next objective was to establish a monthly regime to be applied throughout the year. The initial proposal is that the seasonal changes have a pattern similar to that of the natural hydrologic

Table 1 | Hydrologic Parameters calculated for the Segura River Downstream of the Cenajo Reservoir (DCR) and the Talave Reservoir (DTR) in the Mundo River. Group 1: average monthly discharge in m³/s. Group 2: maximum and minimum moving averages of intervals that vary by duration (days). Group 3: Julian day of the year of maximum and minimum annual discharge. Group 4: frequency and duration (days) of floods and droughts (considered values above the 75th and below the 25th percentiles, respectively). Group 5: variations in discharge and their duration.

	DCR (Segura River)				DTR (Mundo River)			
	Mean	SD	Mean + SD	Mean – SD	Mean	SD	Mean + SD	Mean – SD
Group 1								
October	8.45	2.56	11.01	5.89	1.99	0.82	2.81	1.16
November	10.85	5.38	16.23	5.48	1.98	0.87	2.85	1.11
December	11.52	6.06	17.58	5.46	3.12	3.03	6.15	0.09
January	12.43	6.37	18.80	6.07	3.25	2.78	6.02	0.47
February	13.89	7.27	21.17	6.62	3.06	1.67	4.73	1.40
March	12.57	4.74	17.32	7.83	2.69	1.51	4.20	1.18
April	11.83	3.88	15.71	7.95	2.91	1.53	4.44	1.38
May	11.18	3.71	14.89	7.47	2.16	0.98	3.13	1.18
June	10.16	2.84	13.00	7.32	1.84	0.44	2.28	1.40
July	8.95	2.45	11.39	6.50	1.59	0.16	1.74	1.43
August	8.72	2.31	11.03	6.41	1.54	0.14	1.68	1.40
September	8.44	2.56	11.00	5.88	1.67	0.42	2.08	1.25
Group 2								
Average Max1D	65.83	45.54	111.38	20.29	14.89	15.79	30.68	–0.90
Average min1D	0.65	0.72	1.37	–0.07	0.59	0.46	1.05	0.13
Average Max3D	52.89	37.96	90.85	14.93	11.33	12.48	23.81	–1.15
Average min3D	1.81	1.11	2.92	0.70	0.86	0.28	1.14	0.57
Average Max7D	36.96	22.34	59.30	14.63	8.46	7.73	16.19	0.73
Average min7D	3.37	1.34	4.71	2.03	1.04	0.23	1.26	0.81
Average Max30D	20.66	9.63	30.30	11.03	5.39	3.92	9.31	1.48
Average min30D	6.12	1.69	7.81	4.42	1.39	0.13	1.52	1.26
Average Max90D	16.20	7.92	24.11	8.28	3.98	2.34	6.31	1.64
Average min90D	7.45	2.28	9.73	5.17	1.53	0.14	1.68	1.39
Group 3								
Maximum day	48	130	283	178	15	136	244	121
Minimum day	170	123	321	75	227	174	53	36
Group 4								
Freq. floods	7	3	10	4	7	3	10	4
Duration floods	16	9	26	7	16	9	25	7
Freq. drought	5	4	9	1	5	4	9	1
Duration drought	14	20	35	–6	14	20	35	–6
Group 5								
# increases	173.0	8.0	181.0	165.0	163.0	37.0	199.0	126.0
# decreases	190.0	8.0	198.0	182.0	178.0	31.0	210.0	147.0
Average increase	4.2	1.7	5.9	2.5	0.6	0.4	1.0	0.2
Average decrease	3.9	1.5	5.4	2.4	0.5	0.4	0.9	0.2

regime (unregulated). We used completed (reconstructed) monthly data from natural flow regimes to calculate monthly indices (the relationships between average monthly flow and minimum annual monthly flow for each month).

Initially, this is the point where the correction will be applied based mainly on the habitat simulation results. In the interest of having different options, we calculated two different flow regimes to have negotiation options with stakeholders and to reproduce the inter-annual variability of these rivers with different hydrological regimes in different years. These two regimes will be more demanding, with higher flows for abundant years and the other, less demanding, for dry years. The monthly regimen is built by multiplying the value of the minimum environmental flow by the group of monthly indices. One of the flow regimes, which we place in the least restrictive part of the proposal, is calculated starting from the lowest minimum flow value of those obtained by hydrological methods. At the upper end, another regime is built starting from the minimum flow, which is the highest value of those obtained by hydrological methods.

Therefore, the variations necessary to obtain these two regimes can be done in two ways: (1) As previously explained, by selecting two different minimum flow values, one higher than the other, from among the results obtained by hydrological methods (for example, change of slopes (QBM) and greater increase in slope) and (2) The second applying to the monthly indices a correction in the form of a power that makes them smaller, for example, by taking the square root of all monthly indices as proposed by Palau & Alcázar (2012), see Equation (1).

$$I_m = (Q_{xm}/Q_{\min})^n \quad (1)$$

where n changes from 0.5 to 1; Q_{xm} is the average monthly flow rate for each month; Q_{\min} is the monthly flow rate of the month with the lowest flow rate; n is the index that can vary from 0.1 to 1.

In the correction proposal presented in this article, we start with the first strategy, constructing two regimes from two different minimum flows and then correct with the second strategy, if necessary. Finally, we design two environmental flow regimes, which are the extremes of a range of proposals for valid environmental flow regimes (Richter *et al.* 1997).

2.3. Habitat simulation WUA-Q curve construction

The method used to calculate the relationship between fish habitat and flow (Kennard *et al.* 2000; Armstrong *et al.* 2003; Pyron & Lauer 2004), which was determined through hydraulic simulation, is derived from the application of one of the essential points in the IFIM-PHABSIM method (Bovee 1982; Stalnaker *et al.* 1994; Arthington *et al.* 2006). We used the software River 2D for the hydraulic simulation (Steffler *et al.* 2000) to simulate flow in two dimensions.

To apply methods using habitat simulation in our study area, we carefully selected the rivers' reaches and keystone species. The criteria considered included the selected river reaches and an adequate representation of the mesohabitats in which the selected species for establishing environmental flows are found (Parasiewicz 2007).

The choice of the most adequate flow depends on the biotic components and the habitat they require. Finally, we obtained a representation of WUA for each flow based on the fish habitat, from which different strategic flow values can be established, such as minimum, maximum, or optimal flow (García de Jalón 2003). WUA-flow curves for the two reaches of the study were made to correspond to the fry, juvenile, and adult developmental phases. To simplify the results in the manner proposed by the Spanish hydrological planning instruction, an official methodology instruction approved in Spain (HPR; R.D. 907/2007), values were also obtained for combined WUA-Q curves, which take a percentage of the adult results and another of the predominant fish age classes depending on the time of year. Two seasonal periods were established that we call the wet and the dry seasons. The time from November to April, which we call the 'wet season' and the combined results of the adult and juvenile stages will be considered in that time interval, between May and October, the dry season, the results of the adult and juvenile curves were taken into consideration to select the flows. In this way, we will have a smaller number of results, which simplifies the selection. In the rest of the text, we call these results values for the *wet period* and values for the *dry period*.

2.4. Selection of significant flow values in the WUA-Q curve

One of the most controversial aspects of using the IFIM method is choosing the selected flows from the WUA-Q curve. Often, the significant flow is selected at a point on the curve where there is a marked change with a rapid increase in habitat followed by stabilisation. It is assumed that, above this point, any increase in habitat is associated with a large increase in flow. The

Spanish HPR includes a section on estimating minimum ecological flows and specifies two methods to determine the point on the curve that should be chosen for optimal ecological flow:

- The point on the curve where there is a significant slope change (QBM method).
- The flow that causes a fixed amount of maximum WUA. For a water body that is not highly modified, the valid interval for the minimum ecological flow should produce 50–80% of the maximum WUA.

Given that one of the objectives of this study is to obtain several values to contrast and evaluate the results obtained in the hydrological methodology, we have chosen several flow values within the intervals that have been studied. For each simulation, the values of 50–80% of the maximum WUA of the combined curves have been selected and the flow that produced the change in the curve slope allowed us to critically examine the values obtained with the hydrological methodology.

The wetted area under each flow regime and the depth obtained in the hydraulic simulation can also be taken into consideration to interpret the results. This can be used to examine the distribution of the water surface at a certain depth.

2.5. Correcting the initial monthly regime with the critical values of the flow habitat curve

The monthly distribution of minimum flows obtained by the hydrological methodology will be corrected by analysing the habitat provided by the proposed flow values in the river reach, which seek to produce in each river enough habitat every month and a sufficient percentage of habitable river surface area for fish.

The correction of the monthly regimens (two at the extremes of a valid interval), obtained by hydrological methodology, began by comparing the monthly flow values of the two regimes with the singular or critical flow values of the combined curves, obtained by habitat simulation methods. The process continued counting, in each of the generated regimes, the months in which the proposed flow value did not exceed the flow corresponding to 80% of the maximum WUA of the combined curves, using the result of the wet season curve in the months of November–April and the dry period values in the months from May to October. The same analysis of the monthly flow values is made using the flow corresponding to 50% of the maximum WUA of these curves as a contrast value.

In those months in which the contrast values were not reached, the monthly flow values were corrected in two ways:

- Modifying the coefficient that affects the monthly indices (n in Equation (1)), these vary from 0.5 (value of the square root) to the value of 1.
- In each case, increase the monthly value of specific months until they reach 80 or 50% of the maximum WUA.

We have considered the first way to be more appropriate since a harmonic modification of all the monthly flows was achieved, so we managed to follow changes similar to the natural ones. The second method was more advisable when, despite raising the coefficient to 1, the contrast flow values were not reached. Using the previously mentioned modifications and the contrast values that we have selected, environmental objectives will be achieved by improving river habitat.

The main limitation of this method comes from the difference between the flow that covers the channel section and provides sufficient habitat, and the natural flow circulating in these rivers. Sometimes, due to natural or induced morphological changes, the channel section adopts a morphology that needs a very high flow to cover it and produce sufficient habitat, and this is incompatible with the natural average flows of some months. For this reason, the flows obtained by hydrological methods are far from those that produce high percentages of maximum habitat; this controversial point is developed in more depth in the discussion section.

The proposed method allows for simple approximations to a monthly flow regime; based on the habitat created, the modification of the monthly indices can be taken to a certain point of consensus; the method provides information on the amount of habitat obtained when reaching the maximum modification; this information is relevant and useful to have technical criteria to support future hydrological planning decisions.

3. RESULTS

The comparison between the average reconstructed flow data and the series of recorded data in the same river used as a reference, gauging data similar to natural flow, can be seen in [Figure 2](#). Average reconstructed monthly flows are displayed in [Table 2](#). The DCR flow is 2.63 times higher than UCR. The coefficient of flow increase ranges between 2.01 and 3.45 depending on the year. In the Mundo River, the DTR flows are 1.6 times higher than in UTR, coefficient ranges from 1.17 to 2.28.

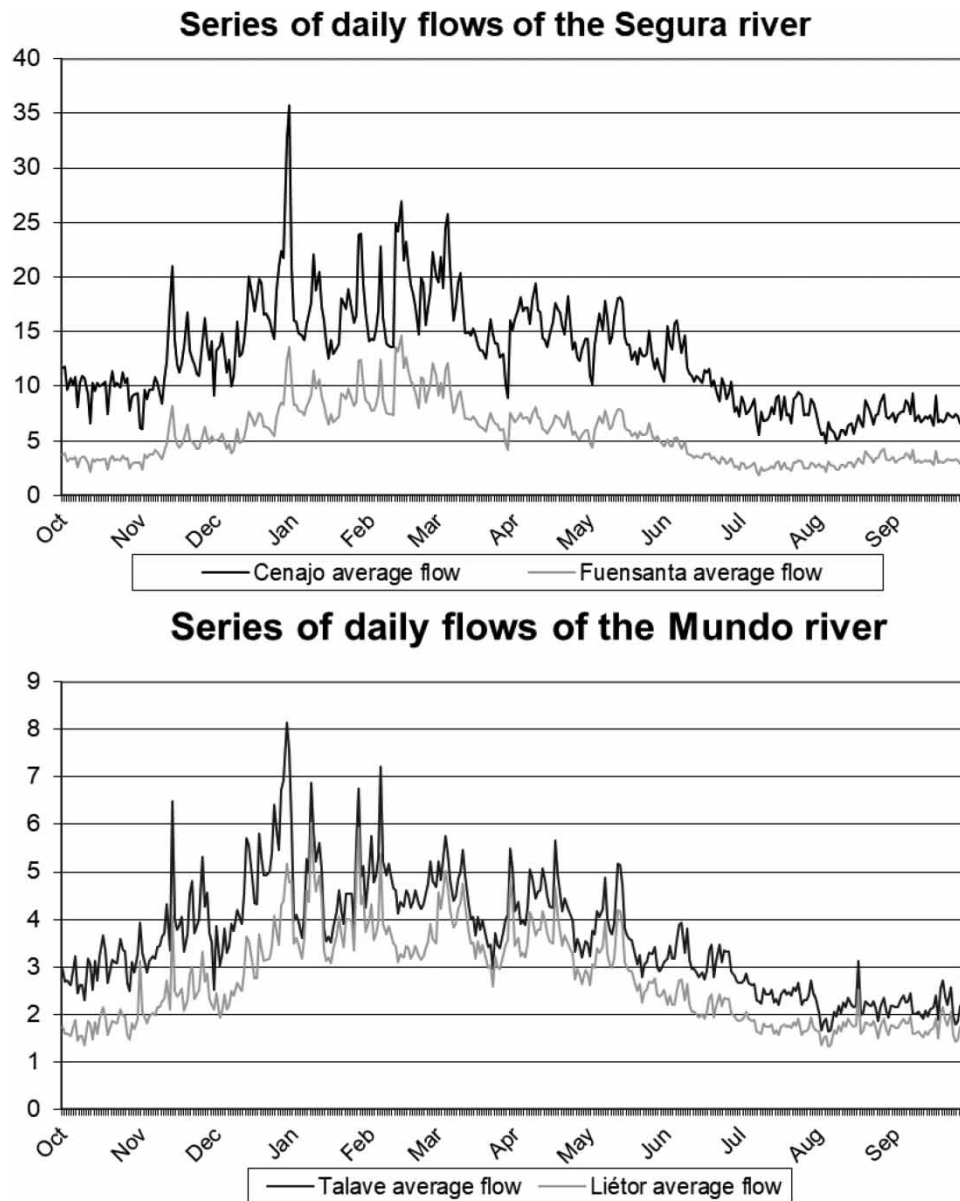


Figure 2 | Daily average flow values in the natural and reconstructed flow regimes: (a) Segura River (Fuensanta, natural regime; Cenajo reconstructed regime); (b) Mundo River (Liétor, natural regime; Talave, reconstructed regime).

3.1. Minimum environmental flow obtained by hydrologic methods

We obtained the minimum value for each data series for a specific interval using the moving average calculations from the daily flow data. As we have explained in the methodology, two criteria were used to choose the minimum discharge: (1) the value where the slope changes and (2) the value with the highest increase in slope (QBM method). For DCR (Segura River), the value where the slope changes is $5.94 \text{ m}^3/\text{s}$ and the value with the highest increase in slope is $2.28 \text{ m}^3/\text{s}$ (OPH-C.H. Segura 2014).

In the Mundo River (DTR), the change in slope is observed at $1.23 \text{ m}^3/\text{s}$ and the highest slope increase is at $0.77 \text{ m}^3/\text{s}$ (OPH-C.H. Segura 2014).

As we have seen in previous paragraphs, the change in slope criteria yielded higher values than the value with the highest increase in slope. Table 3 shows the minimum flow values obtained by the two explained methods and the minimum flow value included in the official documents of the Segura Hydrological Plan (OPH-C.H. Segura 2015).

Table 2 | Average monthly flow (m^3/s) from gauge stations upstream of the reservoirs in the Segura River (UCR) and Mundo River (UTR) and reconstructed values for downstream of these reservoirs (DCR, DTR)

	Segura River			Mundo River		
	UCR	DCR	Ratio	UTR	DTR	Ratio
October	3.20	9.31	2.91	1.79	2.86	1.60
November	4.74	10.36	2.19	2.37	3.56	1.50
December	6.64	13.34	2.01	3.09	5.03	1.63
January	8.75	17.59	2.01	3.86	6.11	1.58
February	10.03	23.56	2.35	3.46	7.89	2.28
March	7.47	18.95	2.54	3.62	6.83	1.88
April	6.49	17.99	2.77	3.33	6.17	1.85
May	6.05	16.06	2.65	2.82	4.61	1.64
June	3.65	11.44	3.13	2.12	3.20	1.51
July	2.65	9.15	3.45	1.72	2.20	1.28
August	3.07	8.49	2.77	1.67	1.95	1.17
September	3.28	9.21	2.81	1.76	2.54	1.44
Average	3.20	9.31	2.63	2.63	4.41	1.61

The ratio between the two values is also presented.

Table 3 | Minimum ecological flow values for two reaches of study, calculated using three hydrologic methods: highest slope of moving averages (QBM), value for change in slope, and the value of the 10th percentile of the daily natural flow series

Method	Moving averages QBM	Moving averages (change in slope)	10th percentile of the daily natural flow series
DCR Segura River (m^3/s)	2.28	5.94	1.6
DTR Mundo River (m^3/s)	0.77	1.23	0.55

3.2. Flow values obtained using hydraulic simulation

Figure 3 shows the WUA-Q curve obtained for the two river sections, for each fish age class and for the combined curves. In the Segura River (DCR), the results of the hydraulic simulation yield a maximum ecological flow for the wet period of $14 \text{ m}^3/\text{s}$ (Figure 3). Other significant values are the flow that produces a marked change in the slope. We observed this value at $6 \text{ m}^3/\text{s}$. In the Mundo River, the flow that produced the maximum habitat for the wet period is $6.5 \text{ m}^3/\text{s}$ and the flow where the slope changes is $3.5 \text{ m}^3/\text{s}$ (Figure 3 and Table 4). These latter two values are higher than the monthly minimum flows circulating in the channel (according to the values reconstructed for the Talave by the Segura Hydrographic Confederation (CHS)). These results may be due to the particular river morphology of these sections, which will be discussed later. Table 4 shows the values corresponding to the optimal, 50 and 80% maximum WUA and the changing slope flows of the combined curves for the Segura River reach, downstream of the Cenajo Reservoir, and the Mundo River reach, downstream of the Talave reservoir. These will be the values used to correct the monthly flow values obtained by hydrological methods.

To simplify the results, we selected two minimum flow values to construct the ecological flow regimes obtained by using hydrologic methods. The monthly flow values were obtained by multiplying the value of the minimum flow by the simple or corrected monthly indices transformed by the coefficients; these are the starting regimes that are going to be corrected (Table 5). To construct the ecological monthly flow regime, we only used calculated flow values in months where they were lower than the natural average monthly flow. For the other months, we used the natural average monthly values.

3.3. Regime correction

Two proposed monthly ecological flow regimes were constructed. These two proposals are the extreme values of a range of possible valid flow regimes. At the upper end would be the regime with the highest monthly flow values and at the lower end

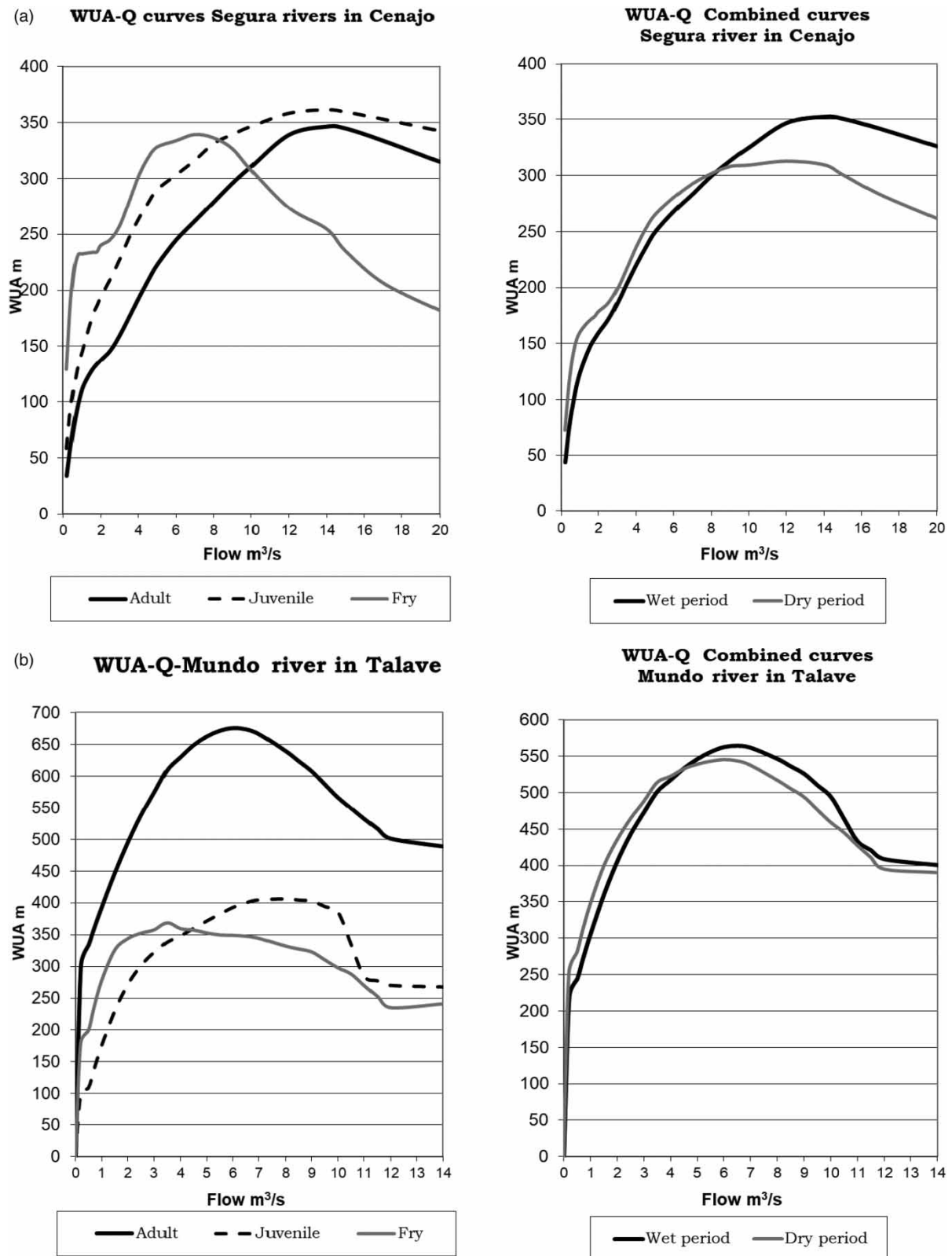


Figure 3 | WUA-flow curve DCR in the Segura River (a, left) and DTR in the Mundo River (b, left) for the three age classes. In the graph on the right the figures show the combined curves, which group the habitat demands of two age classes, one for the dry period and the other for the wet period.

Table 4 | Flow values obtained using hydraulic simulation

Characteristic flow values (m ³ /s)	Optimum flow maximum WUA	Flow corresponding to 80% of max WUA	Flow corresponding to 50% of max WUA	Flow corresponding to 30% of max WUA
UCR Segura River wet period	14	6	2.8	0.6
UCR Segura River dry period	12	4	0.98	0.42
UTR Mundo River wet period	6.5	2.5	1.5	0.42
UTR Mundo River dry period	6	2	0.7	0.12

Optimum flow, maximum value of the WUA-flow curve, values corresponding to 30, 50, and 80% of maximum WUA and minimum flow in the Segura River reach downstream of the Cenajo Reservoir and downstream of the Talave Reservoir in the Mundo River. The values for the dry period and for the wet period are shown.

Table 5 | Flow regimes proposed for the Segura (DCR) and Mundo (DTR) Rivers

Flow regime (m ³ /s)	DCR (Segura River)		DTR (Mundo River)	
	High flow regime	Low flow regime	High flow regime	Low flow regime
October	5.94	2.29	1.23	1.00
November	7.84	3.01	1.24	1.01
December	8.75	3.36	2.16	1.74
January	9.24	3.55	2.23	1.80
February	9.86	3.79	1.98	1.60
March	8.81	3.39	1.73	1.40
April	8.31	3.20	1.89	1.53
May	7.76	2.99	1.41	1.14
June	7.17	2.76	1.14	0.92
July	6.31	2.43	0.99	0.80
August	6.16	2.37	0.96	0.77
September	6.02	2.32	1.05	0.85

The first column shows values obtained by using hydrologic methods and for minimum monthly flow the moving averages (change in slope) result, and the second column shows the values obtained by using hydrologic methods and for minimum monthly flow the moving QBM in the Segura River. The next two columns present results using the same hydrologic method in the Mundo River.

would be the regime with the lowest monthly flow values. As a correction strategy for the monthly flows, the results are defined as follows: the monthly values of the upper regime must reach, the flow values that produce 80% of the maximum WUA of the combined curves in the dry and wet periods in most of the months, and that all the values of the lower regime must reach the value of 50% of the maximum WUA. The changes for the two rivers were as follows:

In the Mundo River, the two proposed regimes started with all the monthly indices raised to the coefficient 0.5, producing the lowest flow results (Figure 4). With these values, none of the months meet the objectives since they do not reach the flow value of 80% maximum WUA during any seasonal periods. Regarding the results when the monthly flow values were compared specifically with the flow value of 50% maximum WUA, some months do not reach this value (1 in the higher regime and 4 in the lower one, Figure 4). This was where the correction was applied by modifying the value of the coefficient that affects the monthly indices. If the monthly indices were raised to 0.7, the lower regime would have failed only in 1 month. The value of this month remained the same even if the coefficient was raised to 1. For that reason, it was proposed that this regime was corrected using the monthly index raised to 0.7 (Figure 5).

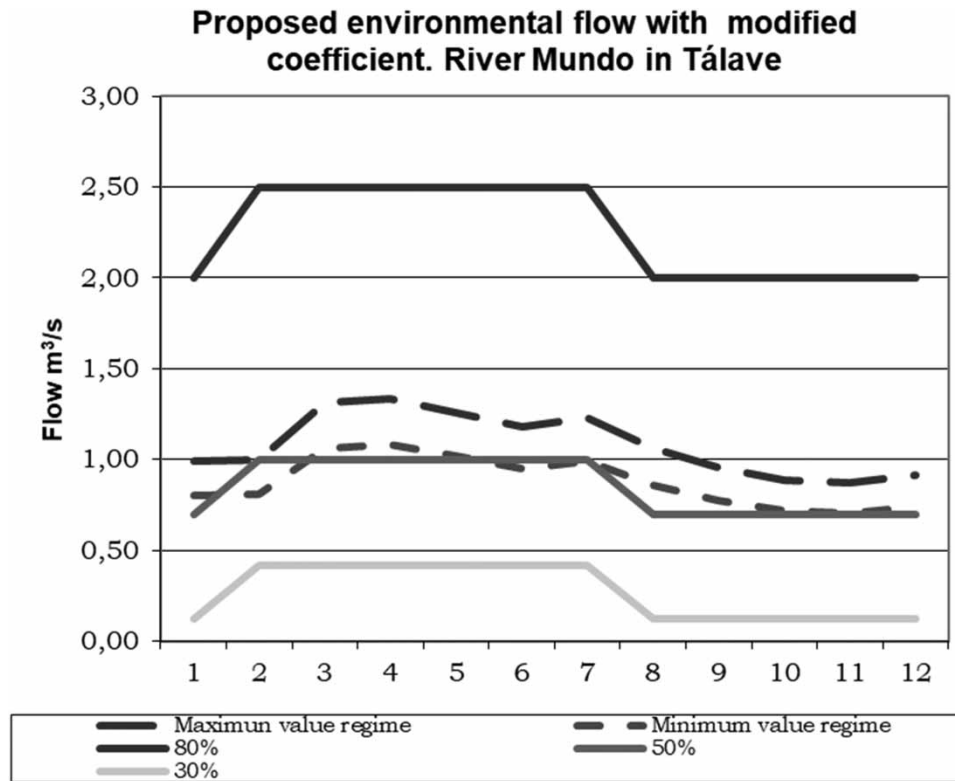


Figure 4 | Initial flow values of the two monthly regimes without changing the coefficient (0.5), which was proposed in the Talave reach of the Mundo River are represented; long dotted lines for the upper regime and short dotted lines for the lower. In grey, from higher to lower intensity colours, the flow values that produce 80% of the 50 and 30% maximum WUA are represented. It is observed that none of the month of the upper regime reach the flow values of 80% of the maximum WUA, for both the wet season and for the dry season. Some months of the lower regime do not reach the contrast value of 50% of the maximum WUA.

The first strategy was not enough to correct the higher regime. Flow values of 80% of the maximum WUA were not reached even when increasing the coefficient to 1, so the second strategy had to be used. We increased the flow values to reach the flow that produced 80% of the maximum WUA, only in the months where these actions were possible. The limiting conditions were the monthly flow values of the natural regime. If we want water to be left for other uses, we cannot propose a regime that is very close to the natural one. Therefore, if we wanted to reach the value that produces 80% of the maximum WUA in this river, we could increase only the 2 months with the highest flow rates. This correction was only possible in the wet period until a flow rate of $2.5 \text{ m}^3/\text{s}$ was reached. The rest of the months were left unchanged. In these months, the flow remained unchanged, so there was a progressive monthly increase until reaching the maximum values of the two highest flow months. In the dry period, no values were changed because if we changed any monthly value to $2 \text{ m}^3/\text{s}$ in the dry period, either the natural monthly mean flow values were exceeded or the corrected values were very close to the natural regime ones. Table 6 shows in the first column that the value of the upper regimen improved with the first strategy and was corrected so that in at least 2 months the value that produces 80% of the maximum WUA was reached.

The corrections in the Segura River were simpler, only the first strategy was used. Initially, the values of the two regimes were constructed with the monthly indices raised to a coefficient of 0.5, so all the values of the higher regime were above the 80% maximum WUA value. However, in the lower flow, 4 months are below 50% of the maximum WUA (Figure 6).

To correct the lower regime, the coefficient was raised to 0.8, ensuring that no monthly flow values of the lower regime were below 50% of maximum WUA (Figure 7 and Table 7).

The most important results of the hydrological analysis are shown in Table 8. This information can complete some components, such as the frequency, magnitude, and duration of flood events of the proposed environmental regime, which complements the monthly regime and makes a more robust proposal.

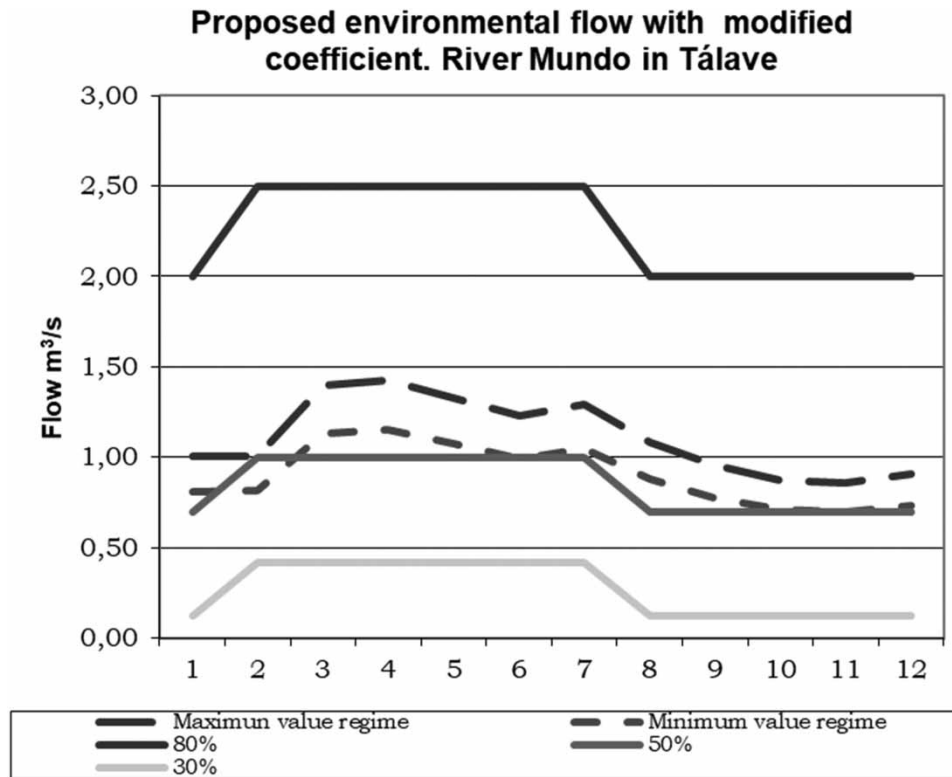


Figure 5 | The values of the two corrected monthly regimes are represented in dotted lines (values coefficient were changed to 0.7). It is observed: none of the month reach the upper regime values of 80% of the maximum WUA, either for the wet period nor for the dry period. In addition, the lower regime was corrected. Also, only one monthly value did not reach the value of contrast of 50% of maximum WUA.

Table 6 | Values of the higher regime of ecological flows in the Talave Reservoir in the Mundo River

	WUA 80% wet period 2.5 m^3/s	WUA 80% dry period 2 m^3/s
Q_{\min} 0.96 m^3/s		
Higher environmental flow	Corrected higher environmental flow regime	Natural flow regime
1.23	1.23	2.05
1.24	1.24	2.06
2.16	2.50	3.57
2.23	2.50	3.69
1.98	1.98	3.27
1.73	1.73	2.87
1.89	1.89	3.12
1.41	1.41	2.33
1.14	1.14	1.89
0.99	0.99	1.63
0.96	0.96	1.58
1.05	1.05	1.74

The regime with the coefficient raised to 1 is shown in the first column. In the second column, the two months in which the values increased to reach the value of 80% of the maximum WUA are marked. The last column shows the natural regime, which limits the ability to correct the values of other months. In grey, the months of the dry period.

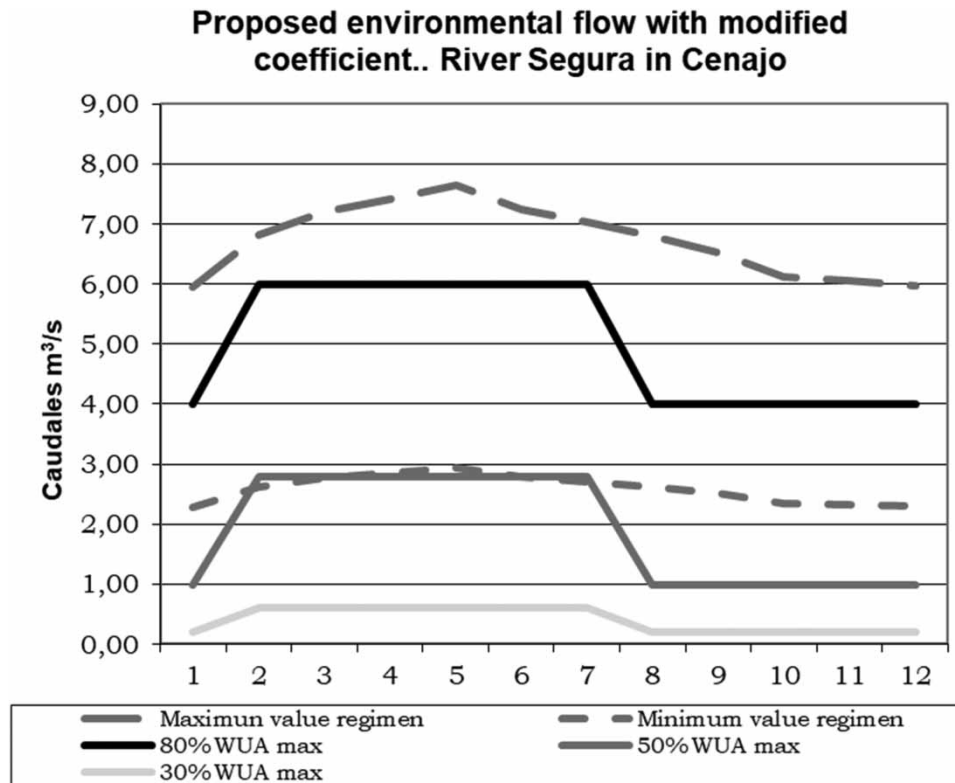


Figure 6 | The values of the two monthly regimes proposed in the Segura River in Cenajo are represented. The values without changing the coefficient 0.5 are represented by the dotted lines, the one is longer the upper regime and the shorter one the lower, in grey colours from highest to lowest intensity, the flow values that produce 80% of the maximum WUA, 50 and 30% are represented. It is observed that the values of 80% of the maximum WUA are reached in all months of the upper regime, in addition, some months of the lower regime do not reach the contrast value of 50% of the maximum WUA.

4. DISCUSSION AND CONCLUSIONS

We followed a ‘bottom-up’ approach (Arthington *et al.* 2006) to establish the environmental flow regime on two river stretches, first calculating the minimum flow and then using this value as the basis for constructing an environmental flow regime with a monthly pattern. The minimum flows in the regime were calculated using two methods, an approach that offered three advantages. Firstly, we were able to obtain several minimum flow values, which provides an option to negotiate with authorities on the minimum flow to be adopted in management programmes (Reed 2008; Paredes-Arquiola *et al.* 2011). Secondly, the results found for the minimum flow can be compared with the natural flows of a reference station during the dry period of the year (Palau & Alcázar 2012). Finally, the values found with one method can be used to improve or correct those obtained with the other (Peñas *et al.* 2013).

In this discussion, we will develop these ideas, starting by assessing what the results obtained by different methodologies provide.

The minimum flows obtained by hydrological methods place us in the order of magnitude of natural low water flows. Habitat simulation can also provide other valuable checks, as it allows us to obtain hydraulic variables of great importance for the survival of fish populations, such as the depth, velocity, and surface area of the water sheet obtained with each flow (Baeza *et al.* 2018).

One advantage of having several values available is that we can compare the results of this study with the official values and recommended methods proposed by the water administrations in Spain. The results obtained for environmental flows can be compared, for instance, with those of the Segura Hydrological Plan (OPH-C.H. Segura. 2015). The value incorporated as the minimum environmental flow in the current Segura Hydrological Plan is the flow that represents the 10th percentile of a long series of annual flow records describing the natural regime. A large difference can be seen if we compare the value of the 10th percentile in the river Segura with the flow intervals that produce sufficient habitat for fish obtained in this study. The minimum flow value in the

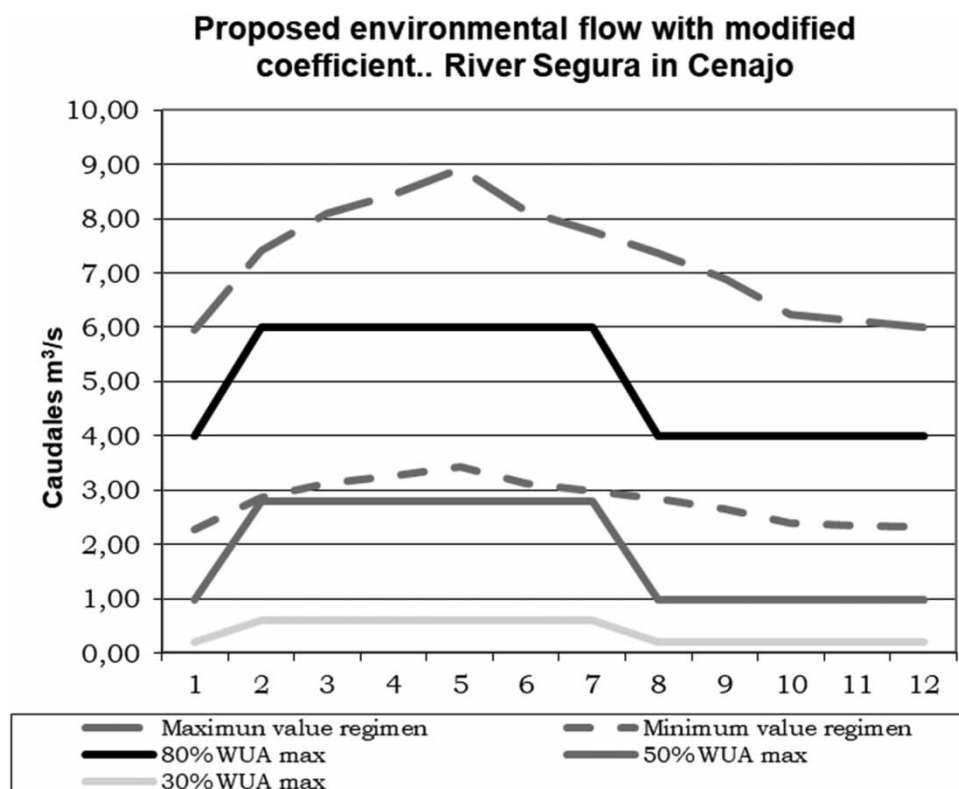


Figure 7 | The values of the two monthly regimes proposed in the Segura River in Cenajo are represented by the dotted lines. The lower regime has been corrected, changing the coefficient to 0.8. It can be observed that no monthly value is below the contrast value of 50% of the maximum WUA.

Table 7 | Values of the lower regime of ecological flows in the Cenajo Reservoir in the Segura River

	WUA 50% wet period 2.8 m ³ /s	WUA 50% dry period 0.98 m ³ /s
Q_{\min} 2.29 m ³ /s		
Lower environmental flow. Coefficient 0.5	Corrected environmental flow regime coefficient 0.8	Natural flow regime
2.29	2.29	8.34
2.62	3.01	11.01
2.77	3.36	12.28
2.85	3.55	12.97
2.94	3.79	13.85
2.78	3.39	12.37
2.70	3.20	11.68
2.61	2.99	10.90
2.51	2.76	10.07
2.35	2.43	8.86
2.33	2.37	8.65
2.30	2.32	8.46

The initial regime with the coefficient raised to 0.5 is shown in the first column. In the second column, regime with the months coefficient raised to 0.8. The increases are sufficient to reach the value of 50% of the maximum WUA. The last column shows the natural regime, which limits the ability to correct the values of other months. In grey, the months of the dry period.

Table 8 | Average values and natural intervals that characterise extreme events in the natural flow regime downstream of the Talave and Cenajo Reservoirs

Characteristic	DCR (Segura River)		DTR (Mundo River)	
	Average value	Interval	Average value	Interval
Floods				
Timing of maximum flood	Day 48 of Julian year (17 February)	Natural interval day 283 (10 October)–178 (28 May)	Day 15 of Julian year (15 January)	244 (4 September)–121 (30 April)
Annual flooding frequency	7	Natural interval day 4–10	7	Natural interval day 4–10
Flood duration in days	16 days	Natural interval 26–7 days	16 days	Natural interval 7–25 days
Magnitude	36.96 m ³ /s	65.83–16.20 m ³ /s	8.46 m ³ /s	3.98–14.89 m ³ /s
Droughts				
Timing of lowest discharge	Day 170 of Julian year (20 June)	Natural interval day 86 (26 March)–254 (14 September)	Day 4 of Julian year (4 October)	Natural interval days 343–31
Annual frequency of lowest discharge	5	Natural interval 1–9	5	Natural interval 1–9
Duration of dry periods	14 days	Natural interval 1–35 days	14 days	Natural interval 1–35 days
Increases and decreases in daily flows				
Daily increase in average discharge	4.2 m ³ /s	3–6 m ³ /s	0.6	1–0.2 m ³ /s
Daily decrease in average discharge	3.9 m ³ /s	2–5 m ³ /s	0.5	0.9–0.2 m ³ /s

These values are presented for their biological value to complement the monthly ecological flow regime proposed, with fundamental components of the flow regime.

current hydrological plan (1.6 m³/s) is well below the flow that produces 80–50% of the maximum WUA (6 and 2.8 m³/s for the wet period, according to our habitat simulation results) and is close to the extreme minimum of 30% of the maximum WUA (0.6 m³/s). In the river Mundo, the hydrological plan value (0.55 m³/s) is also close to the flow rate of 30% of the maximum WUA (0.42 m³/s) and is well below the 80–50% of the maximum WUA (2.5 and 1.15 m³/s, respectively).

Another specification of the Segura Hydrological Plan (OPH-C.H. Segura 2015) on the percentage of habitat to be created for bodies of water with hydrological alteration considers that the environmental flow must generate habitat in the range of 50–30% of the maximum WUA. With the results of the simulations, 50–30% of the maximum habitat percentages in the river Segura are obtained with flows from 2.8 to 0.6 m³/s in the wet season. The flow that produces 30% of the maximum WUA is well below the minimum ecological flow found by the hydrological method, so the lowest value in the interval allowed by the Segura Plan is six times lower than the value obtained in this work (Table 4). This comparison questions the validity of these value intervals allowed by the *Basin Administration* for the restoration of ecological status. Using the simulation method, we have checked the water surface area produced on the river section with a flow of 0.6 m³/s and the results indicate that the available surface area will be greatly reduced with this flow, while the water depth will be too shallow for fish movement. This will lead to water lamina disconnection on certain reaches, making fish movement impossible (Figure 8).

With the hydraulic simulation model, we have also calculated the surface area of water with a depth of 20 cm (the critical value for fish habitat defined by Armstrong *et al.* (2003)) on the river Segura in order to consider how this parameter varies when the flow rate is changed from 6 m³/s (flow rate for 80% of maximum WUA in the wet period) to 0.6 m³/s (flow rate for 30% of maximum WUA), finding values of 3,934 and 3,620 m², respectively.

On the river Mundo, the flows that produce between 50 and 30% of the maximum WUA, according to our habitat simulation results for the wet period, are 1.15–0.42 m³/s. The water surface area and the distribution of depths within the reach were determined for the flows producing 80 and 30% of the maximum WUA in the wet period (2.5 and 0.42 m³/s). The surface area of water with a sufficient depth went from 3,934 to 3,648 m², respectively. The available surface area is not greatly

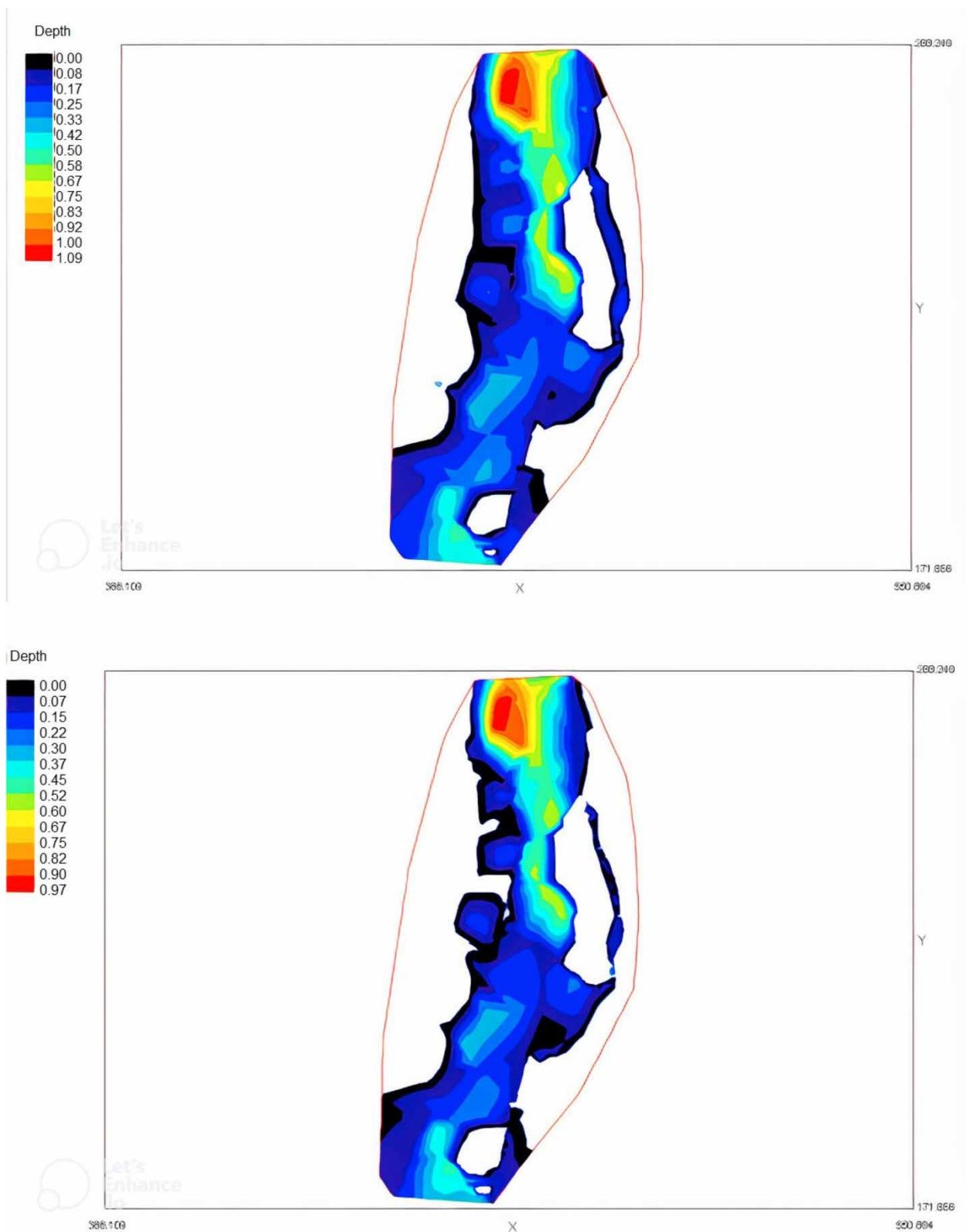


Figure 8 | Distribution of depths and the wetted area in Segura River, Cenajo reach. Up: simulation of 2.5 m³/s of flow and down: simulation of 0.6 m³/s flow. The wetted area over 20 cm loses continuity.

reduced at lower flows, but the flow rate drops to almost 0 and a flow of $0.42 \text{ m}^3/\text{s}$ causes the river section to take on the characteristics of a pool. These results seem to suggest that in this case the most appropriate value is the minimum flow, which produces between 80 and 50% of the maximum WUA and is also the most compatible with the mean natural values and the water basin's management.

We now discuss the relevance of the difference in the minimum flow values obtained with the two methods, hydrological and habitat simulation. The highest values obtained by the two methods for the river Segura do not differ greatly; the highest hydrological flow value being $5.94 \text{ m}^3/\text{s}$, while the flow that produces 80% of the maximum WUA is $6 \text{ m}^3/\text{s}$. On rivers with little seasonal variation and therefore with low coefficients of intra-annual variation of their natural regime (Gustard *et al.* 1992), higher flow values are usually obtained with the hydrological method based on the stabilisation of moving averages. Rivers maintained by strong aquifers do not usually have extreme droughts, with low water flow values that differ little from the average and are similar to the needs of fish species (Baeza & García de Jalón 1997).

This explains the results on the river Segura but not on the river Mundo. The flow that produces 80% of the maximum WUA on the river Mundo is much higher than that obtained with hydrological methods and also than the average natural monthly flow in the driest month. To explain this result, it is necessary to consider both the procedure and the physical environment where the work has been done. One reason is the uncertainty in the location of the maximum or optimum flow in the habitat simulation method due to the uniqueness of the WUA-Q curves, while another is related to morphological factors of the channel, such as the entrenchment ratio of the river section or the width/depth ratio (W/D) (Rosgen & Silvey 1996), which can produce WUA-Q curves that are difficult to interpret. A river with a high entrenchment ratio may need a very high flow to reach its optimum, as it has potentially floodable areas in its lateral flood zone that still create habitat, and this flow is often higher than the usual flows present in the river. On the other hand, rivers with a low entrenchment ratio may present curves in which the optimum value is not reached with the usual natural flows and which are difficult to interpret.

One of the main reasons for this difference in the values on the river Mundo is the modification of the river's morphology on stretches downstream of the Talave Reservoir. The results of the hydraulic simulation depend on the river's morphology when habitat creation is to be estimated and if this is altered by external actions, in this case an unnaturally widened channel, the flows necessary to achieve an increase in habitat will be higher than the natural flows. Only in basins with strong aquifers, which maintain a stable regime in summer with few differences compared to the monthly values for the rest of the year, are natural summer flows compatible with the production of a high habitat surface area, or higher.

Sometimes the value determined as the optimum flow in the simulation method is that which theoretically produces the largest area of habitat, although it is not within the usual range of natural flows, especially in the dry period of the year. Nevertheless, it is a good reference value to try to optimise habitat whenever possible, for instance during periods of the life cycle of fish that are more sensitive to habitat quality.

The minimum flow is the values of greatest interest as a determining factor in river basin management, given that in principle management rules usually stipulate that the flows through a river cannot be less than the minimum ecological flows, even in exceptional circumstances, in order to avoid irreversible damage to the environment. Therefore, the ecological minimum flows must be compared with the usual values of natural low flows and the values obtained by hydrological methods are normally closer to these values.

In the case of the river sections we are studying, we could ask whether the results obtained with the habitat simulation methods are not useful, as is the case with the optimum flow or the flow obtained by changing the slope, because there is not sufficient flow in a natural regime in the months of low water. If this is the case, what is the usefulness of a flow higher than the natural monthly minimum?

The problem arises when the flow that creates sufficient habitat is higher than the natural flow. To answer this, the suggestion in our method is to use the flow values obtained by habitat simulation, which reflect the amount of habitat that we consider should be maintained, to correct some values or as a reference for other times of the year different from the period of lower flow, when there may be sufficient flow to reach these values, and provide the stretch of river with sufficient habitat for fish populations or to carry out certain activities such as movement in the river.

Following this reasoning, the next question to ask is: what objectives do we want to achieve with the proposed full flow regime? If the objective is to maintain the fish population, the next question is: what activities of the biological cycle do we want to facilitate with these flows? In this case, some activities such as wildlife movements or pre-reproductive migrations may occur at times of the year when hydraulic or habitability conditions are sufficient, and then we can propose monthly high

flows in the environmental regime, but only for the months when these processes occur, allowing these activities to take place, with sufficient depth, velocity, and width of the river.

There is an added difficulty in applying habitat simulation methods to morphologically modified water bodies, which does not exclude the need to restore them and propose a valid environmental flow regime. One of the fundamental problems is to find river segments in natural conditions downstream of reservoirs, where the morphological data for the hydraulic simulation can be taken. This is the case of the river Mundo, where the river morphology has changed enormously as a consequence of higher than natural flows, leading to very intense erosion and consequent channel incision (Fischenich & Morrow 2000). As a consequence, the fish habitat has also changed. This situation should lead us to try a different approach to the results of habitat simulation, which our method provides. This extreme case of highly morphologically altered rivers should not interfere with the objective of restoring the ecosystem to the conditions of rivers that have not been highly altered by anthropogenic activities and to propose an ecological flow regime in these places that contributes to increasing the structural complexity, biodiversity, and ecological integrity (Covich *et al.* 1995) of the areas downstream of these structures (Jiang *et al.* 2010).

The ecological status of these areas is relatively poor, especially in the river Mundo, as evidenced by the fish community found in recent sampling (Navarro *et al.* 2010). It is necessary to implement a flow regime closer to the natural flow regime that creates a habitat for fish, which should be the beginning of a restoration with other measures, such as the creation of fish ladders, on stretches where river fragmentation by dams prevents fish movement and morphological restoration actions (Schwindt *et al.* 2019; Owusu *et al.* 2020).

With respect to the main approaches of this work, these are mainly focused on an improvement of the construction of the seasonal regime of ecological flows, with the values obtained by various methodologies. Concerning this, García de Jalón (2003) describes the main techniques used in our country to build the flow regime that begins with the minimum flow value. According to this author, these techniques can be classified into two main groups:

(a) The first takes into consideration the needs of the selected indicator species, assuming different flow requirements of their development stages and (b) In the second group of methods, the natural hydrological values are used and attempts are made to reproduce the natural seasonal changes, in a proposal that copies the natural variation pattern.

The first method has been less used, although it is the basis of an important and very elaborate proposal, the building block methodology (King *et al.* 2002), but out of this complex structure there are few applications and practical examples. Some cases can be found in the scientific literature in which the requirements and temporal needs of the species are used to correct hydrological values (Peñas *et al.* 2013).

Possibly because of the power of the indices of hydrological alteration (IHA) hydrological indicator method (Richter *et al.* 1997) and the facilities for obtaining the regime monthly flow values, the method that reproduces the pattern of the natural regime is the one for which most examples can be found (Tessmann 1980), some with their own name, such as the VMF (variable monthly flow method) (Pastor *et al.* 2014). In Spain, the method described by Palau (Palau & Alcázar 2012), which for some years was adopted as the official one, has also used this hydrological structure to construct the flow values for the rest of the seasons, outside the driest period.

The construction of the environmental flow regime depends very much on the objectives to be achieved, but although the definition of a few values as an environmental flow regime proposal has already been overcome, many proposals still only consider a few values. In a compilation of methodologies adapted to implement the environmental flow regimes in dams (Owusu *et al.* 2020), it was concluded that only a minimum flow is set, or in some cases, generating flows are proposed. Because of these considerations, it is necessary to make progress in the construction of a more consistent monthly regime.

The extensive experience we have with changes in the flow regime and their impact on the functioning of ecosystems leads us to believe that using natural variation to define the variation in the ecological flow regime is a good strategy, but this simple scheme can be improved by nuancing the seasonal changes to fulfil some ecosystem functions.

The proposed method for correcting point values of the environmental flow regime is both simple and sufficiently versatile and improves ecological regimes that are based on natural monthly changes. It can be easily applied to optimise the habitat created for the river's conditional species and contribute to improving the status of animal populations. It is also limited by the values of the natural regime that we use as a check, so that a realistic environmental regime proposal is achieved. It is also adaptable to extreme conditions of variable river morphologies, as it can propose flow values that are efficient in the current conditions of the river, moving them to the time of the year where they fulfil their function, and that are realistic with the natural flows available.

5. IMPLICATIONS FOR PRACTICE

The restoration of a flow regime closer to the natural one, which contributes to the improvement of the ecological state of the fluvial ecosystem, is one of the main challenges in the hydrological planning of areas with high water demands. The number of methods that have been proposed for its calculation is very high (Pastor *et al.* 2014; Tickner *et al.* 2020) and it is sometimes difficult to select the appropriate one, or to interpret results that may be different. There are two main practical issues that this paper addresses. The first is to examine the difficulties in the design and implementation of these hydrological restoration measures from a technical point of view (lack of data, development of methodologies, differences between the minimum flow values found, low seasonal availability of water resources), as well as the steps and strategy to implement them. These strategies should take into account the characteristics of the river where they will be implemented, resolving particularly complex cases such as the implementation of an environmental flow regime in morphologically modified rivers. The water bodies with these conditions are complex to resolve, but also in these complex situations, flow restoration must be ensured in order to contribute to achieving the objectives of the WFD in these highly modified water bodies (Acreman & Ferguson 2010; Ramos *et al.* 2018). The study also provides a solution to resolve situations where the flow values obtained to achieve the optimum fish habitat, or a flow that improves fish habitat, make basin management difficult. The proposal changes the paradigm of optimal habitat flow, using these values as a corrective value rather than as the magnitude on which the flow regime is rigorously based. The habitat flow values can be used to modify a first proposal for a minimum flow rate if there is sufficient water, or to move the flow value along the seasons, to help establish good conditions for some key fluvial processes when more flow is available.

This research advances a simple method to provide a good interpretation of the results for ecological minimum flow in situations where it is difficult to interpret, to check whether the environmental flow regime values are within a range of appropriate values. It improves the establishment of a more robust environmental flow regime that is appropriate for environmental needs and within the range of values available for the management of high-water-demand river basins (King *et al.* 2015). The values obtained for all the components of the environmental regime are used to analyse their compatibility with the total amount of resources available, making the demands of the basin compatible with the conservation of natural values.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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