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Research article

Habitat alteration assessment for the management of environmental flows in regulated basins

J. Pardo-Loaiza, R.J. Bergillos [*], A. Solera, J. Paredes-Arquiola, J. Andreu

Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, 46022, Valencia, Spain

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ABSTRACT

The management of environmental flows is of paramount importance in regulated water resources systems to preserve river ecosystems. This work proposes a methodology to assess habitat alteration in river basins altered by management activities. The methodology is based on the joint application of a basin management model (SIMGES, AQUATOOL) and a model to estimate habitat time series (CAUDECO). CAUDECO is based on the weighted useable areas of the species in their different vital stages that, in turn, depend on the flows in each river stretch and the biological periods of the species. The final output is an indicator of habitat alteration, which is defined ad hoc for this work to relate the habitat suitability under regulated and natural regimes. The methodology was applied to a case study in north-western Spain: the Órbigo River basin. The results in the current management scenario highlight that the ecological flows improve the habitat suitability of several species with respect to natural regime conditions. For instance, the mean values of the habitat time series in the Órbigo River for the brown trout and bermejuela under regulated conditions are 69.6% and 88%; whereas in natural regime they are equal to 55.1% and 72.9%, respectively. Based on these results, eight additional scenarios of ecological flows were tested and their effects on both habitat alteration and water demand reliability were quantified and discussed. It was found that increases in the ecological flows up to 30% do not affect the reliability of water demands and reduce habitat alteration (i.e., lead to values of the habitat alteration indicator closer to 1) for all species present in the river basin. These results highlight that the methodology and indicator of habitat alteration proposed in this paper are useful to support the management of regulated river basins, since they allow assessing the implications of ecological flows on both habitat suitability and reliability of water demands.

1. Introduction

The Brisbane declaration states that an environmental (or ecological) flow regime must be adequate to sustain aquatic ecosystems, which, in turn, support human cultures, economies, sustainable livelihoods and well-being of the population (Arthington et al., 2018). The evaluation of environmental flows in human-altered basins is a complex task that involves many socio-economic and environmental aspects (Sisto, 2009; Stamou et al., 2018; Espinoza et al., 2021; Wineland et al., 2021; Zeiger and Hubbart, 2021; Lu et al., 2022; Yin et al., 2022).

The earliest experiences with environmental flows were performed in the 1940s in the United States (Tharme, 2003). They were later expanded to other countries around the 1970s (Rodríguez-Gallego et al., 2011). Since then, several theories and methodologies have been proposed to estimate ecological flows (Poff and Matthews, 2013; Arthington et al., 2006; Paredes-Arquiola et al., 2014; Hayes et al., 2018; Yan et al., 2018; Al-Jawad et al., 2019; Van Niekerk et al., 2019; Guan et al., 2021, among others).

The physical habitat simulation (PHABSIM) model (Milhous et al., 1984; Milhous, 1990) is one of the most widely used methods to assess ecological flows worldwide. It is part of the Instream Flow Incremental Methodology (IFIM) (Bovee, 1982; Bovee et al., 1998). The PHABSIM model comprises a set of software programs that allows the analysis of changes in the physical habitat due to natural and/or human-induced variations in river flow or channel morphology (Maddock, 1999; Maddock et al., 2004).

PHABSIM is mainly focused on identifying river stretches and species of interest that allow predicting the useable physical habitat for the species in their different life stages (Milhous et al., 1984; Nehring and Anderson, 1993). The usable physical habitat is commonly expressed as Weighted Usable Area (WUA). The WUA is an aggregate measure of the quality and quantity of the physical habitat. It is specific for each river

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[*] Corresponding author.
E-mail address: rbermec@upv.es (R.J. Bergillos).

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flow value and each species in a given life stage (Stamou et al., 2018). Once the WUA is estimated, curves of circulating flow versus WUA (Q-WUA) can be obtained.

The use of Q-WUA curves constitutes the last phase of the IFIM and allows the estimation of habitat time series (HTS) for a given ecological flow regime (Milhous et al., 1984; Milhous, 1990; Benjankar et al., 2018). This technique is, thus, very useful for the analysis of different management scenarios of ecological flow regimes and the comparison with reference conditions (natural flow regime). In complex water resources systems, it is common to analyse species in various river stretches of the basin in order to have multiple representative Q-WUA curves throughout the water resources system (Cheslak and Jacobson, 1990; de Jalón, 2003; Paredes-Arquiola et al., 2014).

Over the past twenty-five years, several methods have been proposed and applied to assess hydrological alteration in regulated basins (e.g., Richter et al., 1996; Richter et al., 1997; Pyron and Neumann, 2008; Martínez Santa-María and Fernández Yuste, 2010; Lu et al., 2018; do Vasco et al., 2019; Pardo-Loaiza et al., 2021; Monico et al., 2022, among others). Two representative examples of these methods are the Indicators of Hydrologic Alteration (Richter et al., 1996) and the Indicators of Hydrologic Alteration in Rivers (Martínez Santa-María and Fernández Yuste, 2010), which are based on the comparison of hydrological variables under regulated and natural conditions. However, for a more comprehensive analysis of the effects of ecological flows on fluvial ecosystems, a comparison of the habitat suitability in regulated regime with the habitat conditions that would have in natural regime is a research gap that need to be addressed.

The main scope of this paper is to propose an integrated methodology for the assessment of habitat alteration in regulated basins. The methodology, which is endorsed by the joint application of water management and habitat simulation models, is applied to a case study in the Órbigo River basin (north-western Spain, Iberian Peninsula). For that, habitat time series are quantified under different management strategies of ecological flow regimes, and the effects of these strategies on habitat alteration and demand reliabilities are discussed.

2. Materials and methods

This work proposes a methodology to quantify habitat alteration that, in turn, allows assessing the effectiveness of ecological flow regimes for the fulfilment of environmental objectives (Fig. 1). For that purpose, a water allocation model is used, and the results are compared to those obtained in natural regime. The hydrological information, along with water demands, infrastructures (reservoirs, canals, pumping), operating rules and minimum flows defined in hydrological plan, represent the current scenario (altered flow regime).

The results obtained for the natural and altered regimes are used by a habitat simulation model that, along with the information obtained from the Q-WUA curves and biological periods of the species in their vital stages, allows the quantification of habitat alteration by means of an indicator defined ad hoc for this work, which is based on the HTS obtained for the species in their different life stages. The methodology also enables the assessment of water demand reliabilities. Different alternatives of ecological flow regimes were simulated to jointly analyse the environmental status of the water resource system and reliability of water demands.

2.1. Data collection

The reference scenario that represents the natural regime requires as input hydrological time series (surface water and groundwater). This information is usually generated through the combination of specific flow measurements and rainfall-runoff models such as Témez (1977), HBV (Bergström, 1976; Bergström, 1995), SAC-SMA (Burnash et al., 1973; Burnash, 1995), GR4J (Perrin et al., 2003), TOPDM (Noto, 2014), or SWAT (Arnold et al., 1998; Srinivasan et al., 1998), among others. On the other hand, information for the current management scenario is usually obtained from the hydrological plan of the study basin and includes data relative to storage and operating rules of reservoirs, flows in channels and river stretches, water demands in the basin (urban, agricultural, industrial, etc.), environmental flow regimes, etc. In the case

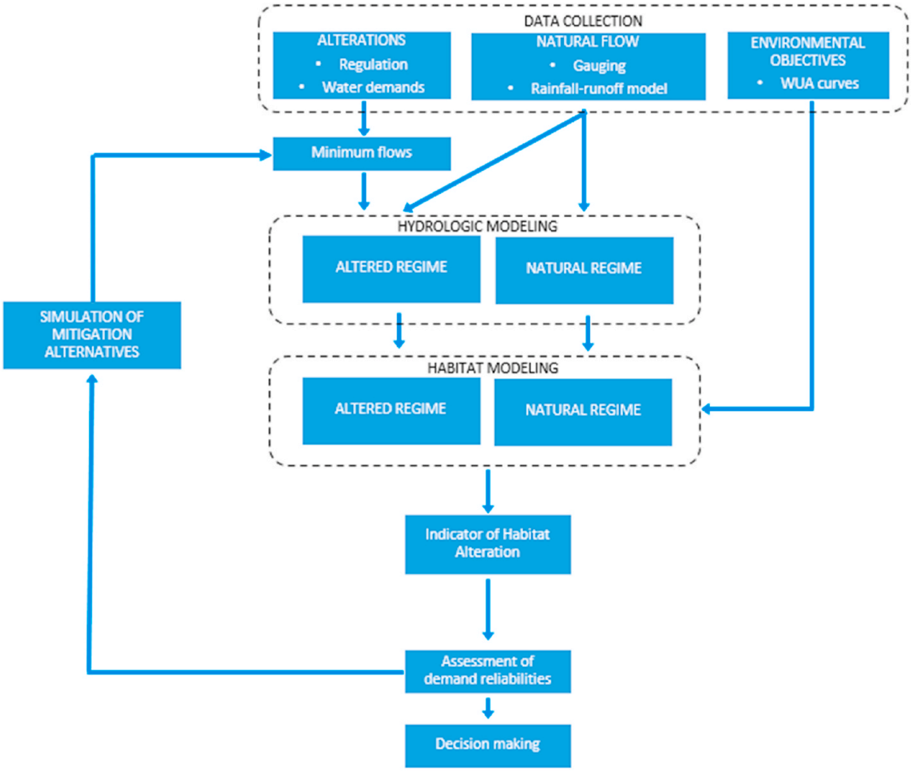


Fig. 1. Flowchart of the methodology proposed and applied in this work.

study analysed in this work, this information is available in the Hydrological Plan of the Duero River Basin (Confederación Hidrográfica del Duero, 2015).

2.2. Water allocation model

To assess the influence of environmental flow regimes on habitat alteration and demand reliabilities, it is necessary to apply a calibrated basin management model. In this work, the SIMGES module (Andreu et al., 2007) of the AQUATOOL Decision Support System (Andreu et al., 1996) was used. AQUATOOL was designed as a user-friendly software platform to support the decision-making processes related to the operation, management and planning of complex water resources systems. This Decision Support System has been used in a broad range of research, consultancy and management studies (e.g., Paredes et al., 2010, 2014; Momblanch et al., 2015, 2017; Suárez-Almiñana et al., 2020, 2022; among others).

The SIMGES module helps solve management problems through a conservative flow network that considers different elements, including natural elements and elements derived from human actions that induce alterations in river flows. SIMGES has been widely applied in previous research works (Lerma et al., 2015; Pedro-Monzonís et al., 2016a; b; Haro-Monteagudo et al., 2017; among others).

2.3. Habitat simulation model

Once the flows have been obtained under natural and altered (regulated) conditions, habitat modelling is carried out using the Q-WUA curves and the biological periods of each species in each vital stage. This allows the computation of HTS under different alternatives of environmental flow regimes.

The CAUDECO model (Momblanch et al., 2014) is a module of the AQUATOOL Decision Support System that estimates habitat time series based on the circulating flows in each water body (obtained with SIMGES), biological period of the species and Q-WUA curves. CAUDECO, therefore, allows the estimation of HTS for different life stages of different species in each river stretch through the river flow values in this stretch. The HTS are obtained based on the following equation:

$$HTS(i) = WUA(Q(i)) * BIOP(i) * L * \sum_{j=1}^{m} i_j\left(c_j(i)\right) \quad (1)$$

where:

HTS(i): value of habitat time series at time *i*.
WUA(Q(i)): value of WUA for the flow *Q(i)* at time *i*.
BIOP(i): biological period function that defines if this species-stage is present (1) or not (0) at time *i*.
L: length of the water body.
I_j: capacity of this species-stage to withstand a pollutant j whose concentration at time i is $c_j(i)$. This term is optional.

These HTS indicate the temporal evolution of habitat available of each species and stage in a water body. CAUDECO also allows the aggregation of HTS of different stages of a species to facilitate the analysis of habitat alteration in each river stretch.

2.4. Indicator of habitat alteration

The results obtained by means of Eq. (1) provide two HTS for each species: one in natural regime and another one in altered regime. Based on these two series, for each species, the following indicator of habitat alteration (IHabA) is defined:

$$IHabA_{(i)} = \frac{\overline{HTS}(i)_{alt}}{\overline{HTS}(i)_{nat}} \quad (2)$$

where:

$IHabA_{(i)}$: Indicator of habitat alteration of species *i*.
$\overline{HTS}(i)_{alt}$: Mean of the HTS of species *i* in altered regime.
$\overline{HTS}(i)_{nat}$: Mean of the HTS of species *i* in natural regime.

This habitat alteration indicator is useful to support the decision-making process and optimize ecological flows considering the habitat preservation and the reliability of water demands, which is detailed in the following section.

2.5. Water demand reliabilities

When a modification is made in an element of a water resources system, it is necessary to analyse the impact of this change on the reliability of water demands. The Spanish water planning regulations (MARM, 2008) establish that, in the definition of ecological flow regime, the influence of the proposed ecological flows on demand reliabilities should be assessed and analysed.

According to the Spanish water planning regulations (MARM, 2008), urban demands are considered satisfied when: (i) the monthly deficit does not exceed 10% of the corresponding monthly demand, and (ii) the sum of deficits in ten consecutive years does not exceed 8% of the annual demand. In the case of agricultural demands, the demand is considered satisfied when: (i) the deficit in one year does not exceed 50% of the annual demand, (ii) the sum of the deficits in two consecutive years does not exceed 75% of the annual demand, and (iii) the sum of the deficits in ten consecutive years does not exceed 100% of the annual demand.

2.6. Study site

The Órbigo River basin is a subsystem that belongs to the Duero River basin. The Órbigo River is a tributary of the Esla River in the northwest of the Iberian Peninsula (Fig. 2). The climate is temperate, and the summers are dry. The annual average temperature is 11.2°C, and the hottest month is July (19.9°C on average). The total area drained by this river is about 5000 km^2 and its length is 162 km. The average annual rainfall in the basin is 725 mm. The rainiest month is November (74 mm), and the driest month is July (23 mm). The mean potential evapotranspiration is 755 mm per year, whereas the average natural flow is 1576 hm^3 per year.

The reservoirs of the Órbigo water resources system have a total regulation capacity of about 373.6 hm^3. The two most important reservoirs are Barrios de Luna and Villameca, which are located at the head of the water resource system. The reservoirs play an important role in preventing floods during the autumn and spring rains, as well as in providing resources during the summer. This means that the reservoirs are often empty at the end of the summer and filled again for the irrigation season (intra-annual regulation cycle).

For this work, a management model of the Órbigo River basin implemented in SIMGES was used. This model, which comprises 52 river sections, was previously calibrated for the elaboration of the Hydrological Plan of the basin (Confederación Hidrográfica del Duero, 2015). Thus, the simulations of the Órbigo basin model carried out in this work for the current management scenario were based on the information of this Hydrological Plan, covering a period of 45 years (1961–2006). The natural regime scenario was obtained considering only the natural contributions; whereas for the current management scenario (altered regime) it was necessary to include demands, reservoirs, etc.

To evaluate HTS in the basin, the available information was collected to apply the CAUDECO model. The Hydrological Plan of the Duero River Basin Agency (Confederación Hidrográfica del Duero, 2015) includes the Q-WUA curves of all species in two stretches of the Tuerto and Órbigo Rivers, which are located in the middle and lower parts of the basin, respectively. Fig. 3 shows the SIMGES model of the Órbigo River

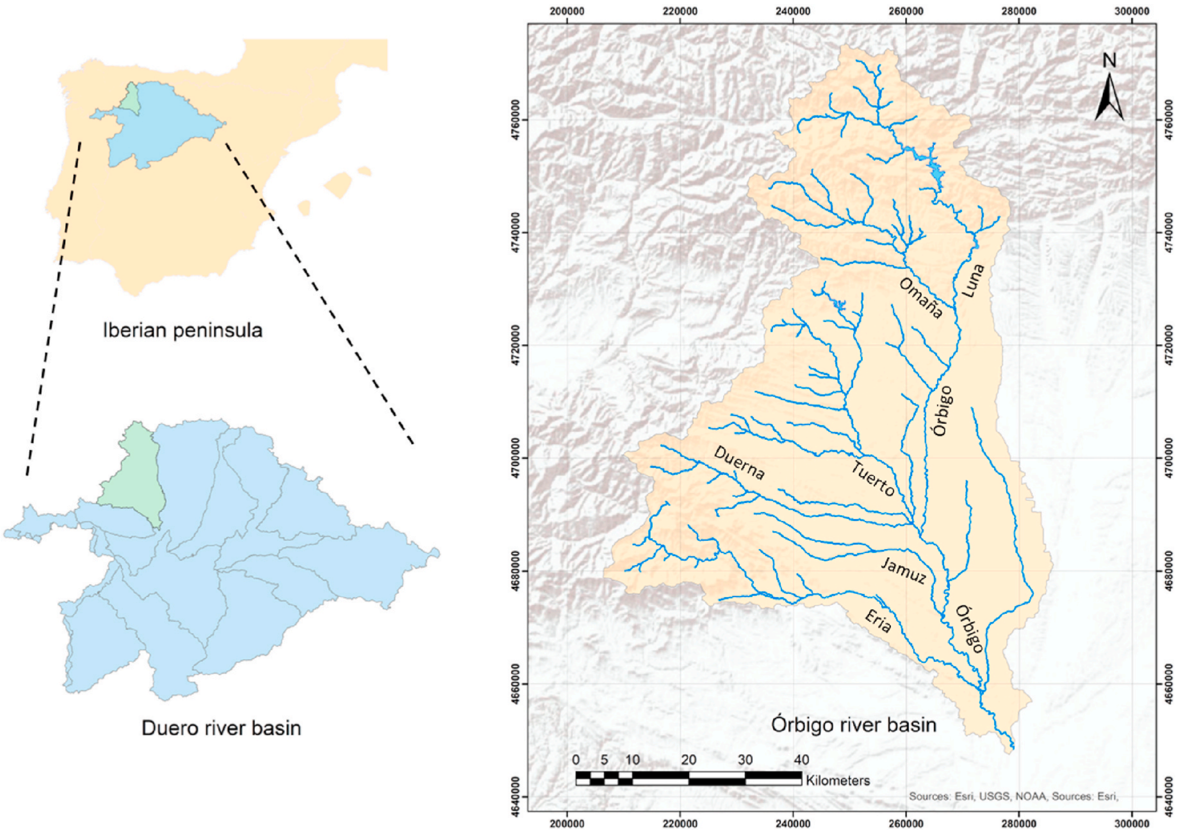


Fig. 2. Location of the Duero and Órbigo River basins (left panel), and main river stretches in the Órbigo River basin (right panel).

basin, indicating the two river stretches analysed for the assessment of HTS.

In the two river stretches analysed, five species were identified: Iberian barbel, brown trout, Iberian nase, Iberian chub and bermejuela. Iberian barbel, brown trout and Iberian nase are present in the two river stretches. The barbel is the most restrictive species in its adult stage since this species demands the greatest flow value in both stretches (Fig. 4). According to the Spanish legislation (MARM, 2008), for the species that do not present a maximum or significant change in slope in their Q-WUA curves, the WUA associated to the 25th percentile value of the series of mean daily flows should be considered as the maximum WUA value. The biological periods of each species, which indicate the temporary presence of the species in each stage, were also considered (Table 1). Finally, the input flow series for the CAUDECO model were the results of the SIMGES model in natural and altered regimes.

3. Results

3.1. Habitat time series

The joint application of the SIMGES and CAUDECO models provided HTS under natural and altered (regulated) conditions. These series can be depicted in square meters or as a percentage of the maximum WUA value. The HTS of the species in the Órbigo river stretch are shown in Fig. 6.

In the case of the Iberian barbel, under regulated conditions, the percentage of habitat is lower than 50% during the summer months and the mean value of the HTS is 72.9%; whereas for natural conditions the average value of the HTS during the simulated period is 87.8%. Thus, the natural regime provides more suitable conditions for the Iberian barbel in the Órbigo river stretch. This pattern is similar for the Iberian nase.

However, the other two species present in the Órbigo stretch of river exhibit an opposite behaviour. As can be observed in Fig. 5, the regulated regime induces higher values of HTS for the brown trout and bermejuela in the Órbigo River. The mean values of the HTS for these species under regulated conditions are 69.6% and 88%, respectively, whereas under natural conditions these values are reduced to 55.1% and 72.9%, respectively.

Fig. 6 depicts the HTS of the species in the Tuerto river stretch in natural and regulated conditions. In this case, the average values of the HTS of the Iberian barbel are quite similar in regulated and natural conditions (82.4% versus 84.4%), thus providing similar conditions in terms of habitat suitability. The comparison of these values with those obtained for the same species in the Órbigo river stretch indicates that the WUA in the Órbigo River (with an average value of the HTS equal to 70.2%) is significantly greater than in the Tuerto River (82.4%). Under natural conditions, the variation in the mean values of the HTS of the Iberian barbel between both stretches is much lower (84.4% in the Tuerto River and 87.8% in the Órbigo River).

Regarding the brown trout and Iberian nase, the HTS values are again similar under regulated and natural conditions, and these values are generally greater than those obtained in the Órbigo river stretch for both natural and regulated conditions. The only exception is the HTS of the Iberian barbel under natural conditions. Finally, as can be observed in Fig. 6, the HTS values of the Iberian chub are significantly lower than those obtained for the rest of species of the Tuerto River. The mean values of the HTS of the Iberian chub are 29.7% and 18.1% under regulated and natural conditions, respectively. Thus, the regulated regime represents more suitable conditions than the natural regime in terms of habitat suitability for this specie.

3.2. Indicators of habitat alteration for the current management scenario

Based on the HTS detailed in the previous section, the indicators of habitat alteration of all species in the two studied river stretches (Tuerto

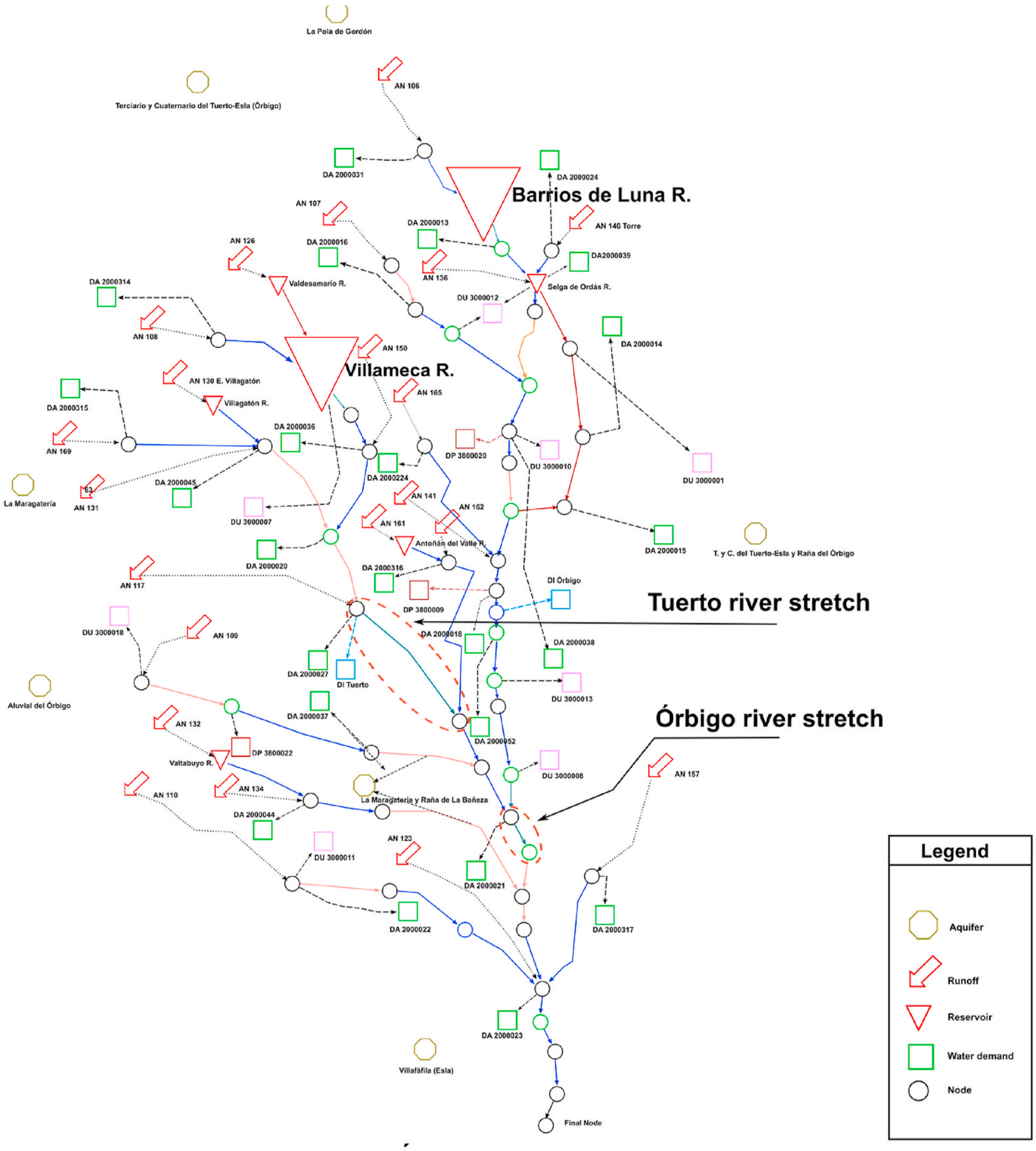


Fig. 3. Topology of the Órbigo River basin generated with the water management model SIMGES. The two river stretches analysed in this work are indicated.

and Órbigo) were calculated through Eq. (2). For a more comprehensive analysis of habitat alteration, three types of indicators were obtained for each species: overall (based on the complete HTS), winter (based on the values of the HTS from October to March) and summer (considering the values of the HTS from April to September). The results are shown in Fig. 7.

In the Tuerto river stretch, it is observed that the overall indicators of habitat alteration of the Iberian barbel, brown trout and Iberian nase are approximately equal to 1. These values indicate that the current ecological flow regime provides similar conditions for the habitat suitability than those that would have under natural (no regulated) conditions. In the case of the bermejuela, the effects of ecological flows are even more positive since the overall indicator of habitat alteration is equal to 1.64, i.e., the current regulated conditions provide, on average, more than 60% of the WUA that would have under natural conditions.

The values of the winter indicators of habitat alteration of the four species in the Tuerto River are about 1. Thus, the habitat suitability is similar under natural and regulated conditions during the winter months. Conversely, during the summer months the indicators of habitat alteration for the four species are further from 1, that is, the differences in habitat suitability between natural and regulated conditions mainly occur during the summer months. These results highlight that the management of ecological flows during those months is essential in terms of habitat suitability. In fact, the WUA of the Iberian chub in the Tuerto River during the summer months under regulated conditions is, on average, almost twice greater than the WUA that would have in natural regime.

In the Órbigo river stretch, the values of the overall indicator of habitat alteration are generally further from one than in the Tuerto river stretch. This could be due to the location of the Órbigo river stretch in the lower part of the basin, where the alterations induced by human activities and water regulation are greater. The seasonal trends of the indicators in both stretches are similar: the habitat alteration is significant in the summer months, whereas during the winter the alteration is comparatively negligible.

The overall indicators of habitat alteration obtained in the Órbigo River indicate that the ecological flows in the current management scenario provide greater habitat suitability for the brown trout and Iberian chub in comparison with the natural regime, but lower habitability for the Iberian barbel and bermejuela, as can be observed in the

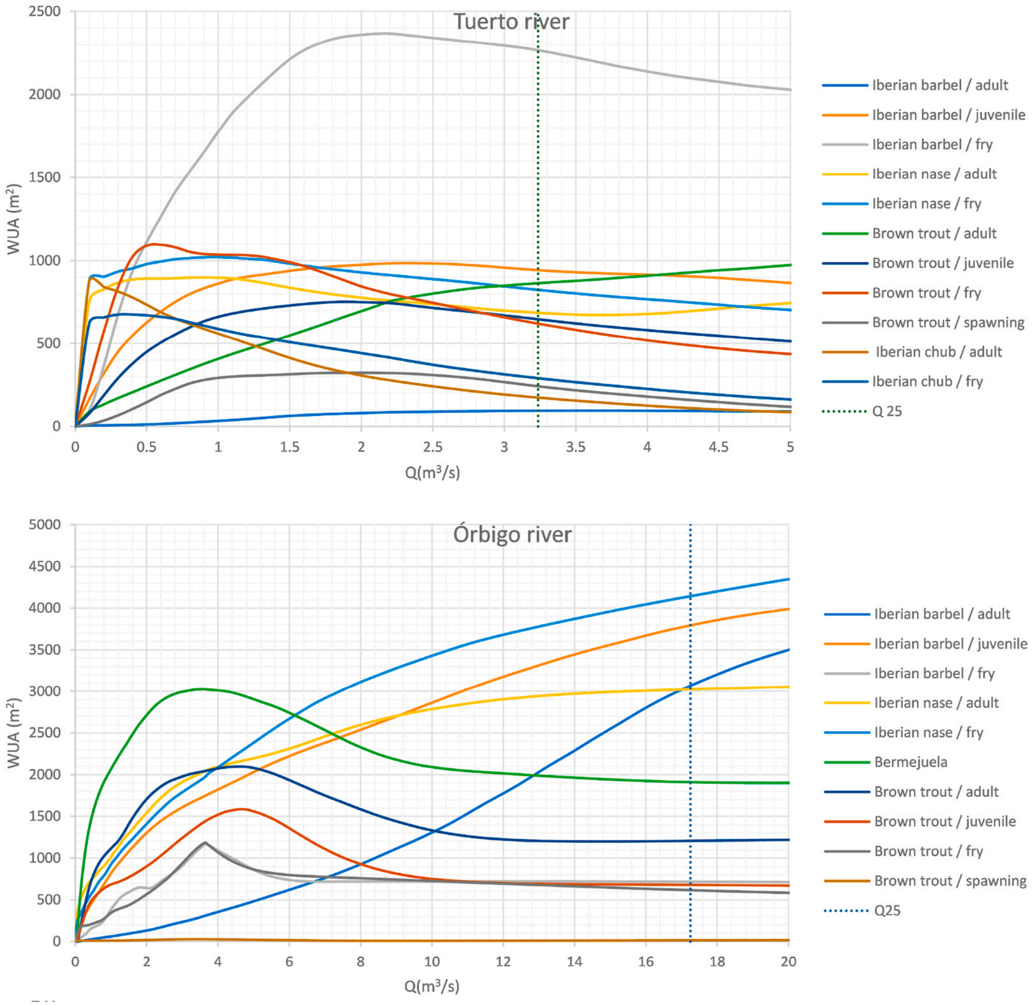


Fig. 4. Q-WUA curves of the species in the Tuerto (upper panel) and Órbigo (lower panel) river stretches in their different life stages.

Table 1
Biological periods of the species in their different life stages.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Iberian barbel adult	1	1	1	1	1	1	1	1	1	1	1	1
Iberian barbel juvenile	1	1	1	1	1	1	1	0	0	0	0	0
Iberian barbel fry	0	0	0	0	0	0	0	1	1	1	1	1
Iberian nase adult	1	1	1	1	1	1	1	1	1	1	1	1
Iberian nase fry	0	0	0	0	0	0	0	1	1	1	1	1
Brown trout adult	1	1	1	1	1	1	1	1	1	1	1	1
Brown trout juvenile	0	0	0	0	0	1	1	1	1	1	1	0
Brown trout fry	0	0	0	0	1	1	1	0	0	0	0	0
Brown trout spawning	0	1	1	1	1	0	0	0	0	0	0	0
Iberian chub adult	1	1	1	1	1	1	1	1	1	1	1	1
Iberian chub fry	0	0	0	0	0	0	0	1	1	1	1	1
Bermejuela	1	1	1	1	1	1	1	1	1	1	1	1

right panel of Fig. 7. Hence, different environmental flow values could be tested to try to improve the habitat suitability under regulated conditions, as it is analysed in Section 3.3.

3.3. Indicators of habitat alteration for different ecological flow scenarios

In this section, the effects of eight new management scenarios of ecological flows on habitat alteration are analysed. The scenarios were defined by varying the values of the current ecological flows from −30% to +50% in ranges of 10% (i.e., −30%, −20%, −10%, +10%, +20%, +30%, +40% and +50%). The indicators of habitat alteration obtained in the Tuerto and Órbigo river stretches for each management scenario are summarized in Fig. 8.

In the Tuerto River, the increases (decreases) in ecological flows induce rises (reductions) in the overall indicators of habitat alteration of the Iberian barbel and brown trout. The effects of ecological flow variations on the indicator of habitat alteration of the Iberian nase are much lower compared to the other species of the Tuerto River. Finally, in the case of the Iberian chub, the greater the ecological flows, the lower the habitat suitability compared to the suitability under natural conditions.

In the case of the Órbigo river stretch, the rise in ecological flow values would generate more suitable conditions for the Iberian barbel

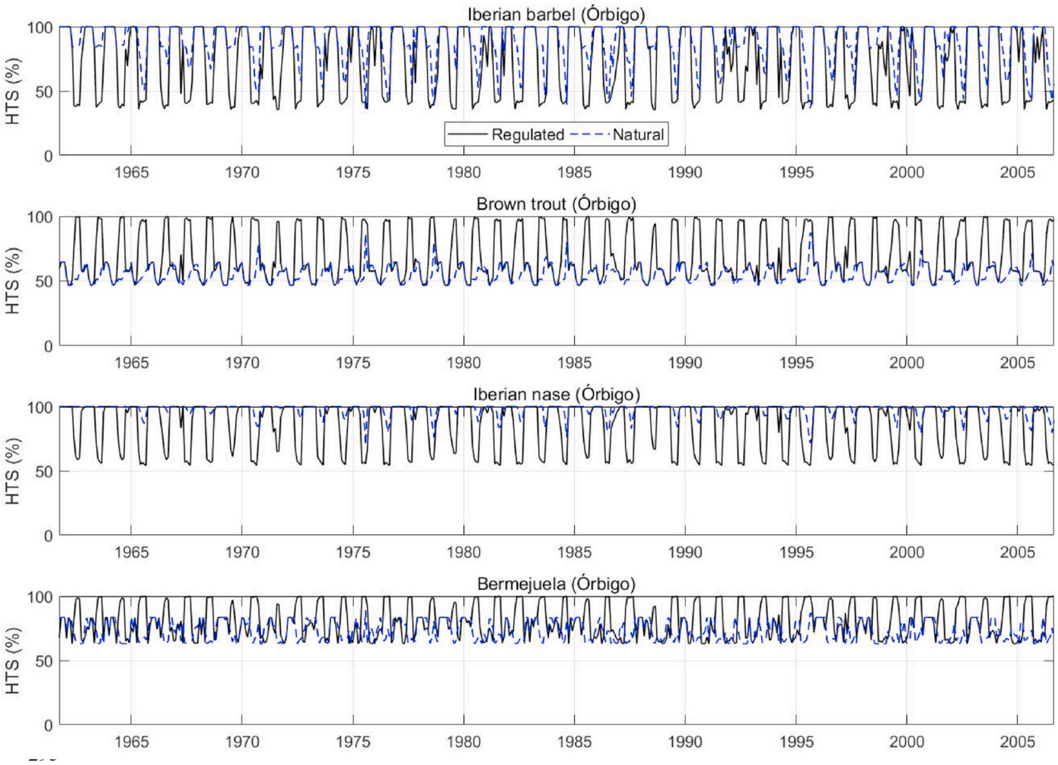


Fig. 5. Habitat time series of the Iberian barbel, brown trout, Iberian nase and bermejuela in the Órbigo river stretch.

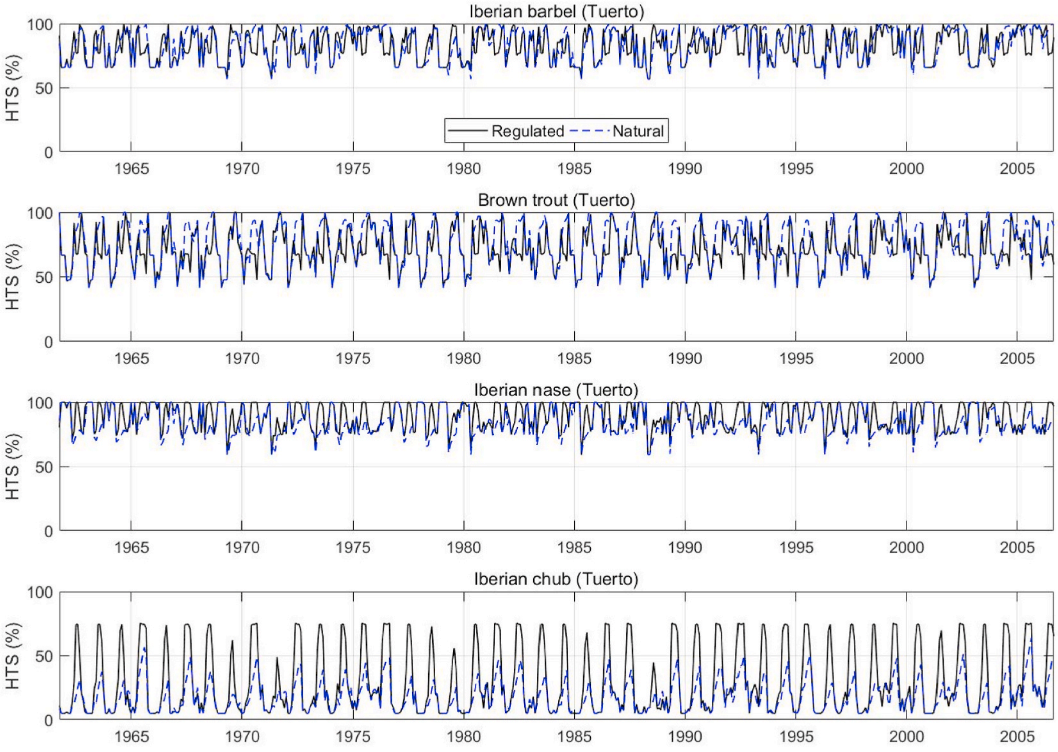


Fig. 6. Habitat time series of the Iberian barbel, brown trout, Iberian nase and Iberian chub in the Tuerto river stretch.

and Iberian nase, but lower average values of the HTS for the brown trout and bermejuela with respect to the current management scenario. However, as can be observed in Fig. 8, the variations in the indicators of habitat alteration induced by the different ecological flow scenarios for the species in the Órbigo River are much lower than those previously reported for the Tuerto river stretch.

Importantly, the increases in ecological flows lead to values of the indicator of habitat alteration of all species present in both river stretches closer to 1, that is, to habitat suitability conditions more similar to those that would have under natural regime.

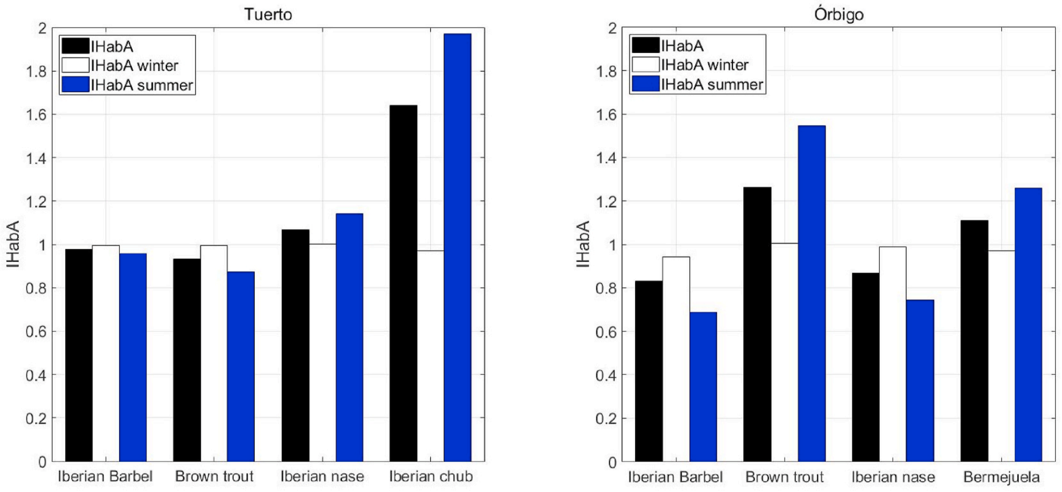


Fig. 7. Overall (black), winter (white) and summer (blue) indicators of habitat alteration of the species in the Tuerto (left panel) and Órbigo (right panel) river stretches.

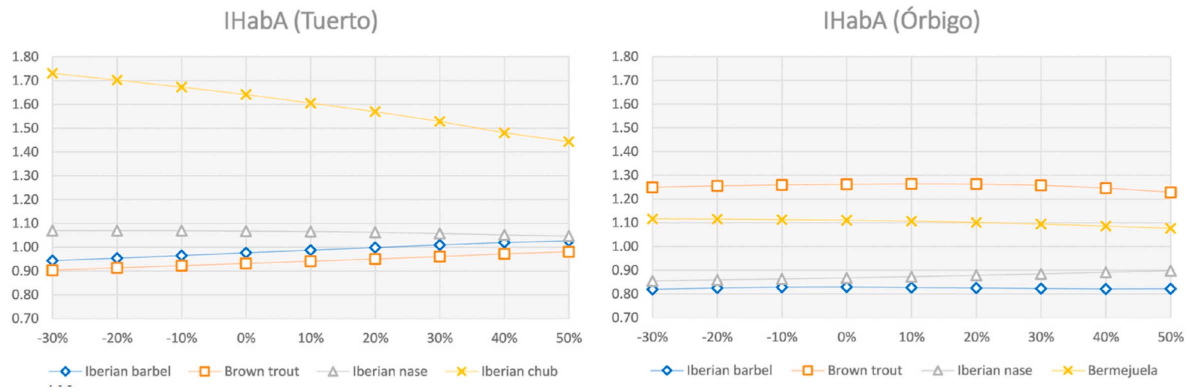
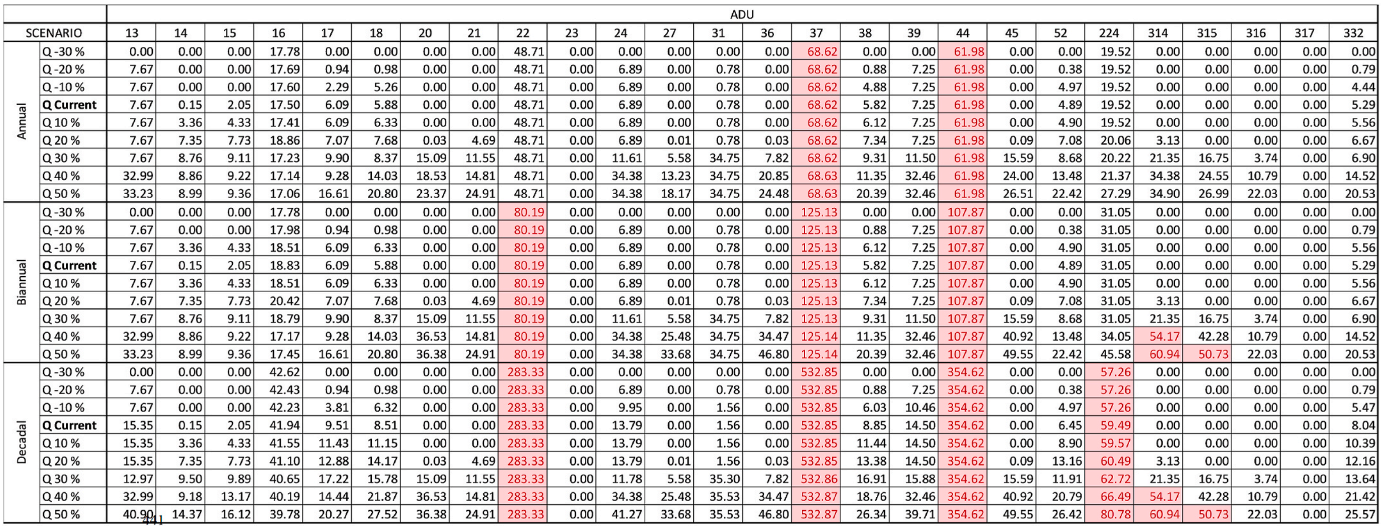


Fig. 8. Overall indicators of habitat alteration of the species in the Tuerto (left panel) and Órbigo (right panel) river stretches for the different scenarios of ecological flows.

4. Discussion

Apart from habitat alteration, it is necessary to analyse and discuss the effects of ecological flow scenarios on the reliability of water demands in the study basin. According to the Spanish water planning regulations (MARM, 2008), among the different water uses, the urban



		ADU																									
SCENARIO		13	14	15	16	17	18	20	21	22	23	24	27	31	36	37	38	39	44	45	52	224	314	315	316	317	332
Annual	Q -30 %	0.00	0.00	0.00	17.78	0.00	0.00	0.00	0.00	48.71	0.00	0.00	0.00	0.00	0.00	68.62	0.00	0.00	61.98	0.00	0.00	19.52	0.00	0.00	0.00	0.00	0.00
	Q -20 %	7.67	0.00	0.00	17.69	0.94	0.98	0.00	0.00	48.71	0.00	6.89	0.00	0.78	0.00	68.62	0.88	7.25	61.98	0.00	0.38	19.52	0.00	0.00	0.00	0.00	0.79
	Q -10 %	7.67	0.00	0.00	17.60	2.29	5.26	0.00	0.00	48.71	0.00	6.89	0.00	0.78	0.00	68.62	4.88	7.25	61.98	0.00	4.97	19.52	0.00	0.00	0.00	0.00	4.44
	Q Current	7.67	0.15	2.05	17.50	6.09	5.88	0.00	0.00	48.71	0.00	6.89	0.00	0.78	0.00	68.62	5.82	7.25	61.98	0.00	4.89	19.52	0.00	0.00	0.00	0.00	5.29
	Q 10 %	7.67	3.36	4.33	17.41	6.09	6.33	0.00	0.00	48.71	0.00	6.89	0.00	0.78	0.00	68.62	6.12	7.25	61.98	0.00	4.90	19.52	0.00	0.00	0.00	0.00	5.56
	Q 20 %	7.67	7.35	7.73	18.86	7.07	7.68	0.03	4.69	48.71	0.00	6.89	0.01	0.78	0.03	68.62	7.34	7.25	61.98	0.09	7.08	20.06	3.13	0.00	0.00	0.00	6.67
	Q 30 %	7.67	8.76	9.11	17.23	9.90	8.37	15.09	11.55	48.71	0.00	11.61	5.58	34.75	7.82	68.62	9.31	11.50	61.98	15.59	8.68	20.22	21.35	16.75	3.74	0.00	6.90
	Q 40 %	32.99	8.86	9.22	17.14	9.28	14.03	18.53	14.81	48.71	0.00	34.38	13.23	34.75	20.85	68.63	11.35	32.46	61.98	24.00	13.48	21.37	34.38	24.55	10.79	0.00	14.52
	Q 50 %	33.23	8.99	9.36	17.06	16.61	20.80	23.37	24.91	48.71	0.00	34.38	18.17	34.75	24.48	68.63	20.39	32.46	61.98	26.51	22.42	27.29	34.90	26.99	22.03	0.00	20.53
Biannual	Q -30 %	0.00	0.00	0.00	17.78	0.00	0.00	0.00	0.00	80.19	0.00	0.00	0.00	0.00	0.00	125.13	0.00	0.00	107.87	0.00	0.00	31.05	0.00	0.00	0.00	0.00	0.00
	Q -20 %	7.67	0.00	0.00	17.98	0.94	0.98	0.00	0.00	80.19	0.00	6.89	0.00	0.78	0.00	125.13	0.88	7.25	107.87	0.00	0.38	31.05	0.00	0.00	0.00	0.00	0.79
	Q -10 %	7.67	3.36	4.33	18.51	6.09	6.33	0.00	0.00	80.19	0.00	6.89	0.00	0.78	0.00	125.13	6.12	7.25	107.87	0.00	4.90	31.05	0.00	0.00	0.00	0.00	5.56
	Q Current	7.67	0.15	2.05	18.83	6.09	5.88	0.00	0.00	80.19	0.00	6.89	0.00	0.78	0.00	125.13	5.82	7.25	107.87	0.00	4.89	31.05	0.00	0.00	0.00	0.00	5.29
	Q 10 %	7.67	3.36	4.33	18.51	6.09	6.33	0.00	0.00	80.19	0.00	6.89	0.00	0.78	0.00	125.13	6.12	7.25	107.87	0.00	4.90	31.05	0.00	0.00	0.00	0.00	5.56
	Q 20 %	7.67	7.35	7.73	20.42	7.07	7.68	0.03	4.69	80.19	0.00	6.89	0.01	0.78	0.03	125.13	7.34	7.25	107.87	0.09	7.08	31.05	3.13	0.00	0.00	0.00	6.67
	Q 30 %	7.67	8.76	9.11	18.79	9.90	8.37	15.09	11.55	80.19	0.00	11.61	5.58	34.75	7.82	125.13	9.31	11.50	107.87	15.59	8.68	31.05	21.35	16.75	3.74	0.00	6.90
	Q 40 %	32.99	8.86	9.22	17.17	9.28	14.03	36.53	14.81	80.19	0.00	34.38	25.48	34.75	34.47	125.14	11.35	32.46	107.87	40.92	13.48	34.05	54.17	42.28	10.79	0.00	14.52
	Q 50 %	33.23	8.99	9.36	17.45	16.61	20.80	36.38	24.91	80.19	0.00	34.38	33.68	34.75	46.80	125.14	20.39	32.46	107.87	49.55	22.42	45.58	60.94	50.73	22.03	0.00	20.53
Decadal	Q -30 %	0.00	0.00	0.00	42.62	0.00	0.00	0.00	0.00	283.33	0.00	0.00	0.00	0.00	0.00	532.85	0.00	0.00	354.62	0.00	0.00	57.26	0.00	0.00	0.00	0.00	0.00
	Q -20 %	7.67	0.00	0.00	42.43	0.94	0.98	0.00	0.00	283.33	0.00	6.89	0.00	0.78	0.00	532.85	0.88	7.25	354.62	0.00	0.38	57.26	0.00	0.00	0.00	0.00	0.79
	Q -10 %	7.67	0.00	0.00	42.23	3.81	6.32	0.00	0.00	283.33	0.00	9.95	0.00	1.56	0.00	532.85	6.03	10.46	354.62	0.00	4.97	57.26	0.00	0.00	0.00	0.00	5.47
	Q Current	15.35	0.15	2.05	41.94	9.51	8.51	0.00	0.00	283.33	0.00	13.79	0.00	1.56	0.00	532.85	8.85	14.50	354.62	0.00	6.45	59.49	0.00	0.00	0.00	0.00	8.04
	Q 10 %	15.35	3.36	4.33	41.55	11.43	11.15	0.00	0.00	283.33	0.00	13.79	0.00	1.56	0.00	532.85	11.44	14.50	354.62	0.00	8.90	59.57	0.00	0.00	0.00	0.00	10.39
	Q 20 %	15.35	7.35	7.73	41.10	12.88	14.17	0.03	4.69	283.33	0.00	13.79	0.01	1.56	0.03	532.85	13.38	14.50	354.62	0.09	13.16	60.49	3.13	0.00	0.00	0.00	12.16
	Q 30 %	12.97	9.50	9.89	40.65	17.22	15.78	15.09	11.55	283.33	0.00	11.78	5.58	35.30	7.82	532.86	16.91	15.88	354.62	15.59	11.91	62.72	21.35	16.75	3.74	0.00	13.64
	Q 40 %	32.99	9.18	13.17	40.19	14.44	21.87	36.53	14.81	283.33	0.00	34.38	25.48	35.53	34.47	532.87	18.76	32.46	354.62	40.92	20.79	66.49	54.17	42.28	10.79	0.00	21.42
	Q 50 %	40.90	14.37	16.12	39.78	20.27	27.52	36.38	24.91	283.33	0.00	41.27	33.68	35.53	46.80	532.87	26.34	39.71	354.62	49.55	26.42	80.78	60.94	50.73	22.03	0.00	25.57

Fig. 9. Maximum annual, biannual and decadal deficits of the agricultural demand units of the Órbigo River basin for the different ecological flow scenarios. The deficit values that represent reliability failure are marked in red.

demands always have priority in the supply of the available water. For this reason, this water use was not compromised in any of the analysed scenarios. On the contrary, the agricultural demands were the most affected water demands by ecological flow variations.

Fig. 9 summarizes the maximum annual, biannual and decadal deficits of the agricultural demand units (ADUs) in the Órbigo River basin for the different ecological flow scenarios analysed in the previous section. The deficit values that represent reliability failure are marked in red. Under current management conditions, there are four ADUs that experience reliability failures: ADU22, ADU37, ADU44 and ADU224. Two of them (37 and 44), which are located in the middle-lower part of the basin (Fig. 10), exhibit failures of the three reliability criteria (annual, biannual and decadal).

These reliability failures are also obtained in the scenarios with lower ecological flows. Thus, a reduction in such flows has not any positive effect in terms of water demand reliability in the study basin. In fact, as can be observed in Fig. 9, ecological flows can be increased up to 30% without any negative affection to the reliability of agricultural water demands in comparison with the current management rules. However, increases in the ecological flows between 40% and 50% induce reliability failures of two additional ADUs: ADU 314 and ADU 315 (Fig. 9), which are located in the upper part of the basin (Fig. 10).

Therefore, the increase in ecological flows until 30% would allow the maintenance of the same water demand reliability fulfilments of the current ecological flow regime (Fig. 9) and reduction in habitat alteration of all species present in the basin with respect to the natural regime conditions (Fig. 8).

5. Conclusions

In this paper, a methodology to assess habitat alteration in regulated basins is presented. The methodology comprises water allocation and

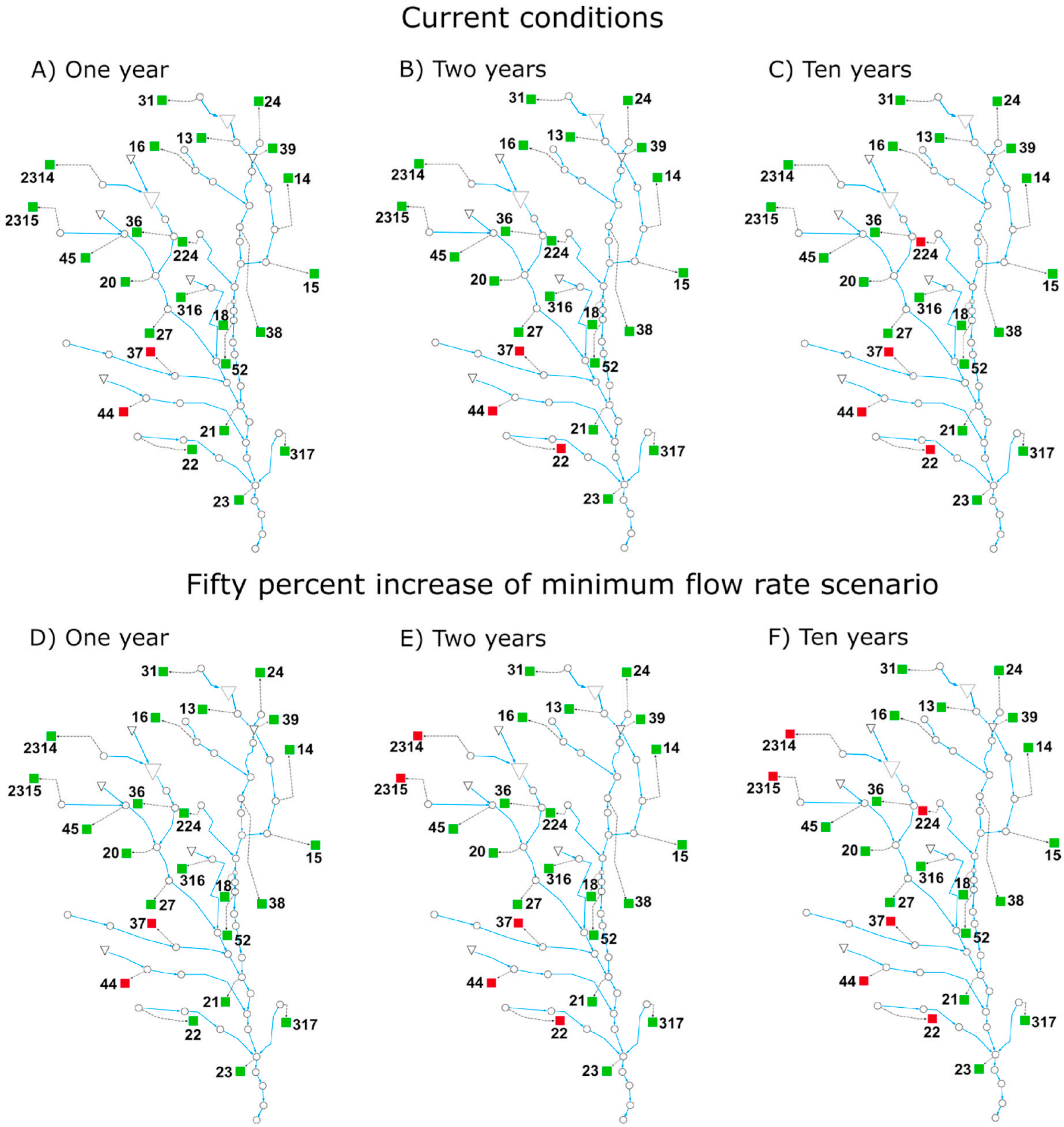


Fig. 10. Spatial distribution of the agricultural demand units in the topology of the model generated in SIMGES. The demand units without (with) reliability failures are indicated in green (red). A), B) and C) show the one-year, two-year and ten-year results of the current management scenario, whereas D), E) and F) depict the results of the scenario with an increase in the ecological flows equal to 50%.

habitat simulation modelling to provide indicators of habitat alteration of the species present in the basin. These indicators are based on the relationship between the habitat time series in regulated and natural conditions. The methodology was applied to the Órbigo River basin (north-western Spain).

The habitat time series and the indicator of habitat alteration were assessed for the current management scenario of ecological flows. It was found that the habitability under the current regulated conditions for half of the species present in the basin is more suitable than the habitability they would have under natural conditions. Thus, ecological flows induce positive effects on these species. The improvements in the habitability are mainly concentrated in the summer months. These results confirm the paramount importance of ecological flows management since they can help provide habitat conditions even better than those in natural regime.

For this reason, eight new management scenarios were defined by varying the ecological flows values from −30% to +50% in ranges of 10%. The results obtained indicate that increases in ecological flow values induce improvements in the habitat suitability of some species and reduce the habitat alteration of all species of the Órbigo River basin.

The implications of ecological flows on supplies to water demands were also quantified and allowed us to conclude that: (i) reductions in ecological flows up to 30% have not any positive effect on the water demand reliability, (ii) ecological flows can be increased up to 30% without any negative affection to the reliability of water demands, and (iii) rises in ecological flow values between 40% and 50% would lead to reliability failures in two agricultural demand units more compared to the current management conditions.

The main contribution of this work is the proposal of a methodology to quantify habitat alteration, which represents a helpful tool for the management of ecological flows in regulated basins. After the application of the methodology to a case study, it was found that: (i) ecological flows can improve habitat suitability compared to natural conditions, and (ii) increases in environmental flows up to 30% reduce the habitat alteration of all species and do not affect the reliability of water demands.

To extend the proposed methodology to other regulated basins, it would be required to have data and information on the water resources management and the species of the basin to properly apply the water allocation and habitat simulation models. The assessment, analysis and mitigation of the effects of climate change on habitat alteration and reliability of water demands represent research challenges to be addressed in the future.

Credit author statement

Jesús Pardo-Loaiza: Methodology, Software, Investigation, Writing – original draft preparation. **Rafael J. Bergillos**: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft preparation, Supervision. **Abel Solera**: Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Javier Paredes-Arquiola**: Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Supervision. **Joaquín Andreu**: Conceptualization, Writing – review & editing; Project administration, Funding acquisition

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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