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Coupling hydrological, habitat and water supply indicators to improve the management of environmental flows

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ABSTRACT

Highly regulated basins have traditionally required management practices to mitigate the negative environmental impacts and ensure human well-being. This paper proposes and assesses environmental and water supply deficit indicators to assist in the management of environmental flows (e-flows). For that, a water allocation model is applied, and hydrological alteration, habitat alteration and water supply indicators are quantified, normalized and integrated into a general basin management indicator. This basin management indicator is analyzed for four management approaches and seven e-flow scenarios in the Júcar River Basin (eastern Spain). Hydrological alteration indicators show a less pronounced alteration in the river sections located upstream of the basin while a higher alteration in the downstream sections. As for the habitat indicators, they experience an improvement compared to the natural regime. Based on the values of the basin management indicator, the best e-flow scenario to adopt in the Júcar River Basin is selected. The indicators proposed in this work are useful for supporting decision-making regarding the planning and management of e-flows in regulated river basins worldwide.

1. Introduction

Water resources are of great importance for socioeconomic development, food production, and environmental conservation. Thus, its exploitation is a vital matter for the development of humanity (He et al., 2018). Rivers' value has been emphasized by humans as agricultural, industrial and domestic consumption of water increases (Karr and Chu, 2000; Wang et al., 2023).

Anthropogenic impacts have generated changes in the flow regime in most river systems. Due to the combined impact of the heterogeneous distribution of water resources, climate change, increasing water demand, and regulation due to anthropogenic activity, rivers have shown a statistically significant hydrological change compared to the natural regime (Peñas and Barquín, 2019; Xie et al., 2022). The climate change scenarios indicate a reduction in natural water resources over the 21st century (Huang et al., 2021; Kourgialas, 2021).

The assessment of river flows is critically relevant as they constitute the basis for water resources planning, decision-making, and operation of related infrastructures (Hannah et al., 2011; Poff and Matthews, 2013; Kapetas et al., 2019). Alterations in the components of the flow regime involving its variability, seasonality, water quality, and ecosystem degradation have a potentially significant impact on ecosystem function and structure, and on riverine physical and chemical processes (Arévalo-Mejía et al., 2020; Song et al., 2021; de Girolamo et al., 2022). These impacts are generally reflected in terms of hydrological alteration, habitat alteration and water supply reliability (Behboudian et al., 2021a, 2021b). This explains the growing concern for river conservation and the need for a better understanding of large-scale water cycle processes to ensure better economic development, and water food and energy security (Tharme, 2003; Long et al., 2019; Van Niekerk et al., 2019; Liang et al., 2021).

Methods for assessing and monitoring stream changes are needed to adopt more ecological water management strategies (Conesa-García et al., 2022; Qian et al., 2021). In line with these needs, an approach that has been used is the implementation of environmental flows (e-flows), which establish the quantity and flow regime necessary to maintain the components, functions, processes, and resilience of aquatic ecosystems that provide goods and services to society (Arthington et al., 2018;

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Kumar and Jayakumar, 2021; Joseph et al., 2021).

These e-flows should reproduce the temporal variability of the river in its natural state (Paredes-Arquiola et al., 2014; Ahn et al., 2018). Owing to the growing awareness of the importance of river systems and the assessment of their general condition, an ever-expanding field of research devoted to assessing e-flows at different spatial and temporal scales has been established (Hayes et al., 2018; Al-Jawad et al., 2019; Guan et al., 2021).

To estimate the degree of hydrological alteration that an ecosystem may be exposed to, it is necessary to implement quantitative assessments of anthropogenic changes in hydrology (Richter et al., 1996). Different methods have been carried out to evaluate this alteration (e.g., Richter et al., 1996, 1997; Henriksen et al., 2006; Monk et al., 2007; Belmar et al., 2011; Eng et al., 2017). All are based on the comparison between the hydrological regime in its current situation and the natural regime, which represents the situation without any anthropogenic intervention. Two of the most used methods to monitor hydrological alteration in the Iberian Peninsula are the indicators of hydrological alteration (IHA) (Richter et al., 1996) and the indicators of hydrological alteration of rivers (IAHRIS) (Fernández et al., 2012; Arévalo-Mejía et al., 2020). Despite the use of diverse hydrological indicators, different challenges remain to select the best indicators for streamflow research and to understand the relevance of each indicator for the biotic communities and the ecological integrity of the river systems, whilst the studies facing those challenges at the national or regional perspective are scarce (Carlisle et al., 2017; Fornaroli et al., 2020).

One of the widespread methods to evaluate the influence of the flow regime on river biota is the application of the physical habitat simulation technique. This technique was developed in the frame of the Instream Flow Incremental Methodology (IFIM), which was originally defined as “a decision-support system designed to help natural resource managers and the constituencies determine the benefits or consequences of different water management alternatives” (Bovee, 1982; Bovee et al., 1998). Although some limitations have been regarded about the IFIM and the physical habitat simulation, there have been relevant advances in the models, and the majority of their purported shortcomings have either been or are in the process of being addressed (Reiser and Hilgert, 2018). The physical habitat simulation remains one of the most widely applied, and jurisdictionally recognized analytical tools for assessing instream-flow-related issues (Tharme, 2003; Martínez-Capel et al., 2017; Reiser and Hilgert, 2018).

In such a technique the habitat suitability is evaluated through habitat simulation models that couple hydraulic modeling in a representative river reach with habitat suitability models developed on experimental data and expert-knowledge (e.g., Muñoz-Mas et al., 2018, 2019; De-Miguel-Gallo et al., 2019) to describe the ecological requirements of aquatic species according to their life stage or activity (Paredes-Arquiola et al., 2013; Miguel et al., 2016).

The main objective of this article is to present a novel methodology for jointly assessing the effects of minimum e-flows on hydrological alteration, habitat alteration and water supply reliability in highly regulated systems. This evaluation is presented in terms of environmental and water deficit indicators to support decisions on management practices applied to e-flows. The proposed methodology offers the transposition and integration of two of the most important methodologies applied in the field of e-flows to water resources management: the IFIM methodology and the IHA. That is, it allows the habitat assessment in a flexible way for one or more aquatic species and the evaluation of hydrological alteration for different management scenarios. The integration of these criteria with the assessment of reliability in urban and agricultural supplies in a decision support system offers wide possibilities in the field of water resources management and is potentially transferable to any region globally.

2. Methodology

The methodology consists of 3 major steps (Fig. 1). The first step is creating and calibrating a water allocation model of the basin. Secondly, the calculation of a set of indicators of hydrological alteration, habitat alteration and water supply reliability throughout the river basin under several scenarios with different minimum e-flows. And the third step is the definition of a decision-making function that allows to combine the indicators considered into a general basin management indicator. This indicator was used to evaluate four management approaches and seven scenarios of minimum e-flows.

A primary task of this methodology is the collection of input data for the water allocation model; mainly, physical characteristics (e-flows, reservoir characteristics, water demands, etc.) and dam operation rules. Once the input data are prepared, the implementation and calibration of the water allocation model are carried out. Then, the model is able to simulate minimum flow scenarios and to estimate alteration indicators. For that, it is first necessary to compute the natural flow regime, as the basis to estimate the hydrological and habitat alteration indicators that, along with water supply reliability, constitutes the general basin management indicator.

2.1. Water allocation model

2.1.1. Natural flow regime

The release of the natural regime allows the generation of flow series presenting the conditions without any regulation. This is used as a baseline to assess the extent of present and future interactions and the degree of alteration in the basin. The natural regime restitution is established by omitting all components presenting a regulation to obtain natural flow series.

The natural regime simulation was carried out in this work with the SIMGES water allocation model. It is a module of AQUATOOL, a Decision Support System (DSS) designed for water resource systems planning and management (Andreu et al., 1996). It is regularly used in the Spanish River Basin Agencies and other countries (Argentina, Brazil, Italy, Mexico, etc.) and delivers assets to assist in the analysis of different water management issues (e.g., Alamy Filho et al., 2014; Lerma et al., 2015; Monico et al., 2022; Pardo-Loaiza et al., 2022a, 2022b; Paredes et al., 2010; Momblanch et al., 2015; Pedro-Monzonís et al., 2016).

2.1.2. Minimum e-flow scenarios

In general, e-flows in river basins help to establish uniformity of water uses and maintain ecosystem functionality. They should maintain the functionality and structure of the associated aquatic and terrestrial ecosystems sustainably, thereby contributing to the achievement of good ecological status of rivers. In Spain, the Water Planning legal norm establishes how the minimum flows, as well as other components of the flow regime, should be defined and implemented (MARM, 2008).

In the SIMGES water allocation model, seven scenarios of minimum e-flows were simulated (by multiplying the current minimum e-flow values by 0.25, 0.5, 0.75, 1, 1.25, 1.5, and 1.75) to analyze their effects on the hydrological alteration, habitat alteration and water supply deficits.

2.2. Hydrological alteration indicators

Monitoring the hydrological alteration is a way to assess the impact of any change occurring in the climate and/or a hydrological system (Arévalo-Mejía et al., 2020). Several methodologies have been developed to quantify the degree of hydrological alteration in river basins (e.g., Fernández et al., 2012; Poff et al., 1997; Richter et al., 1996). The method adopted in this work was based on the IHA proposed by Richter et al. (1996) and developed by *The Nature Conservancy* (2009). These indicators were evaluated, normalized and grouped using a python code developed ad hoc for this work (Table 1).

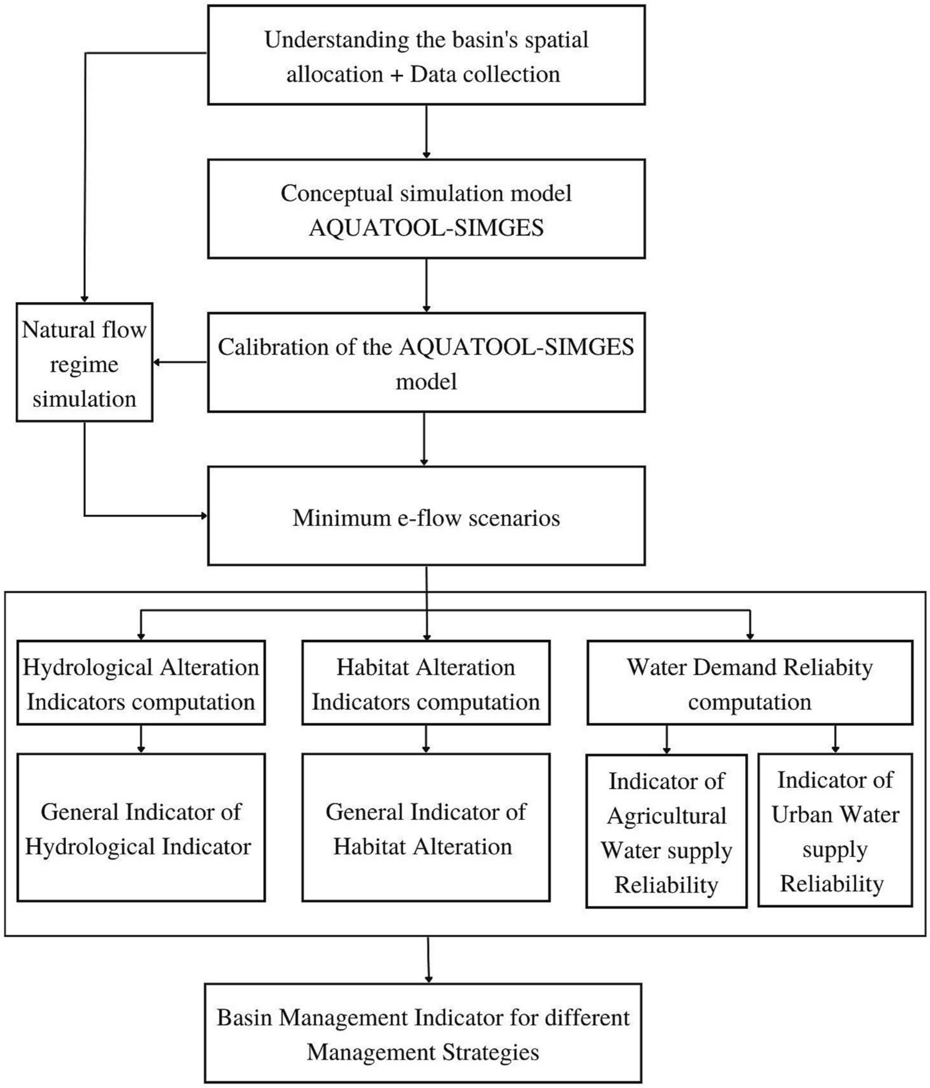

Fig. 1. Flow chart of the methodology proposed in this work.

The normalization of IHA was performed on an interval ranging from zero to one, where zero corresponds to maximum alteration and one to no alteration. The normalization involved the application of the following equations:

$$\textbf{if} -\mathbf{1} \le \textbf{IHA} \le \mathbf{0}; \boldsymbol{IHA_n} = \textbf{IHA} + \mathbf{1} \tag{1}$$

$$\textbf{if IHA} > \mathbf{0}; \boldsymbol{IHA_n} = \frac{\mathbf{1}}{(\textbf{IHA} + \mathbf{1})} \tag{2}$$

2.2.1. *General indicators of hydrological alteration*

After computing the IHA, they were classified and grouped into five indicators. This classification was made considering the interrelation between the type of variable and the factors involved in the evaluation of each indicator (Table 2). The five indicators were calculated as a weighted average of the indicators considered in each group (Eq. 3).

$$\begin{gathered}\textbf{GIHA}_\textbf{J} = \sum \textbf{c}_\textbf{i} {*} \textbf{IHA}_{\textbf{n,i}} \\ \sum \boldsymbol{c_i} = \mathbf{1}\end{gathered} \tag{3}$$

where $\mathrm{IHA}_{n,i}$ are the hydrological alteration indicators considered (Table 2), and c_i are the weighting factors assigned to each indicator.

Ultimately, a general indicator of hydrological alteration was obtained for each river reach, combining the five GIHA. The weighting factor attributed to each of the five GIHA depends on its importance in the studied basin (Eq. 4).

$$\begin{gathered}\boldsymbol{IHA_{g,i}} = \sum \boldsymbol{k_j} {*} \boldsymbol{GIHA_j} \\ \sum \boldsymbol{k_j} = \mathbf{1}\end{gathered} \tag{4}$$

where k_j is the weighting factor of each of the obtained indicators and i refers to the river reach.

Once the general indicators were calculated, a classification by intervals was applied, consisting of four degrees of hydrological alteration (Table 3).

2.3. *Indicators of habitat alteration*

The interrelation of anthropogenic activity, vegetation, topography, geology and climate emphasizes their impact on habitat conditions and requires the evaluation of habitat alteration in river ecosystems. In this work, the assessment of the habitat was carried out through indicators of habitat alteration (HabAIs), defined as the ratio of the average habitat time series (HTS) under altered and natural flow regimes (Eq. 5).

$$HabAI = \frac{average\ (HTS_{alt})}{average\ (HTS_{nat})} \tag{5}$$

Table 1
Indicators of hydrological alteration (Richter et al., 1996).

The magnitude of monthly hydrological conditions	**Winter**	IHA1	October
		IHA2	November
		IHA3	December
		IHA4	January
		IHA5	February
		IHA6	Mars
	Summer	IHA7	April
		IHA8	May
		IHA9	June
		IHA10	July
		IHA11	August
		IHA12	September
Magnitude and duration of annual external hydrological conditions	**Low flow**	IHA13	Annual minima 1-day means
		IHA14	Annual minima 3-day means
		IHA15	Annual minima 7-day means
		IHA16	Annual minima 30-day means
		IHA17	Annual minima 90-day means
		IHA18	Number of zero flow days
		IHA19	Base flow rate
	High flow	IHA20	Annual maxima 1-day means
		IHA21	Annual maxima 3-day means
		IHA22	Annual maxima 7-day means
		IHA23	Annual maxima 30-day means
		IHA24	Annual maxima 90-day means
Timing of annual hydrological extremes		IHA25	Julian date of each annual 1-day minimum
		IHA26	Julian date of each annual 1-day maximum
Frequency and duration of high and low pulses		IHA27	Number of low pulses
		IHA28	Duration of low pulses
		IHA29	Number of high pulses
		IHA30	Duration of high pulses
Rate and frequency of changes in hydrological conditions.		IHA31	Rise rates
		IHA32	Fall rates
		IHA33	Number of hydrological reversals

Table 2
Groups of indicators of hydrological alteration used to evaluate water management scenarios in the Júcar River Basin.

	$GIHA_J$	$IHA_{n,i}$
Magnitude of monthly winter hydrological conditions	J = 1	*i* = 1,2,3,4,5,6
Magnitude of monthly summer hydrological conditions	J = 2	*i* = 7,8,9,10,11,12
Magnitude and duration of annual hydrological minima	J = 3	*i* = 13,14,15,16,17,18,19,25
Magnitude and duration of annual hydrological maxima	J = 4	*i* = 20,21,11,23,24,26
Frequency and duration of pulses and changes in hydrological conditions	J = 5	*i* = 27,28,29,30,31,32,33

2.3.1. *Habitat time series (HTS)*

The CAUDECO program, a module of the AQUATOOL DSS, was designed to calculate the HTS in river sections for different species and life stages (Paredes-Arquiola et al., 2013). The required input data are the flow time series in each river section, which can be obtained with SIMGES, the curves that relate the weighted usable areas (WUA) with river flows (Q), and the bioperiods of the species. In this work, the HTS were obtained for the natural and altered flow regimes.

Table 3
Hydrological alteration status according to the $HAI_{g,i}$ value.

Range	Status
0.75 – 1	Slightly altered
0.5 – 0.75	Moderately altered
0.25 – 0.5	Altered
0 – 0.25	Very altered

The HTS were calculated according to the following equation:

$$\boldsymbol{HTS(i) = WUA\ (Q(i))*BIOP(i)*Long} \tag{6}$$

where HTS(i) is the value taken by the habitat time series at time i; WUA (Q(i)) is the value of the WUA curve for flow Q(i) at time i; BIOP(i) is a function defining whether this stage of the species is present at time i (BIOP = 1) or not (BIOP = 0); and Long is the length of the water body.

2.3.2. *General indicators of habitat alteration*

Once the HabAIs were calculated, they were classified and grouped into indicators representing each of the target species in each river section. Therefore, this indicator consists of the weighted average of the habitat alteration indicators of the different life stages (or size class) for a given species (Eq. 7).

$$\begin{gathered}\boldsymbol{GHabAI_j = \sum c_i * HabAI_{n,i}}\\ \boldsymbol{\sum c_i = 1}\end{gathered} \tag{7}$$

where $HabAI_{n,I}$ are the indicators of habitat alteration obtained for each stage, and c_i are the weighting factors assigned to each stage.

Finally, a general habitat alteration indicator was derived for each river section, combining the different GHabAIs (Eq. 8):

$$\begin{gathered}\boldsymbol{HabAI_{g,i} = \sum k_j * GHabAI_j}\\ \boldsymbol{\sum k_j = 1}\end{gathered} \tag{8}$$

where $GHabAI_j$ are the grouped indicators obtained for each species, k_j are the weighting factors assigned to each species, and i refers to the river section.

The habitat alteration in each river section was evaluated as follows: if the indicator is less than 0.5, it is considered that the habitat alteration is very pronounced compared to the natural regime. If the indicator is between 0.5 and 1, it is assumed that the situation of habitat alteration is reasonable at the time scale of the hydrological cycle. If the indicator is greater than 1, then the general habitat suitability is better than in the natural flow regime.

2.4. *Water supply reliability*

The water supply reliability indicators were obtained based on the maximum deficit percentage provided by the SIMGES model. This deficit percentage is defined as the difference between demand and supply, divided by demand. According to the Spanish Water Planning Regulations released in 2008 (MARM, 2008), the urban water demand is considered satisfactory when the monthly and decadal deficits do not exceed 10% of the monthly water demand and 8% of the annual water demand, respectively. The agricultural water demand is considered satisfactory when the annual, biannual and decadal deficits do not exceed 50%, 75%, and 100% of the annual water demand, respectively.

To normalize the water supply reliability indicators, it was considered that the maximum deficit for the different water demand units corresponds to a 0 value. In contrast, the minimum deficit (no deficit) corresponds to 1. Based on these range of values, a linear interpolation was made to normalize the different water supply reliability indicators.

2.5. Basin management indicator

To combine the general indicators of hydrological alteration, habitat alteration, and reliability of agricultural and urban water supply, a decision-making function was proposed to generate a basin management indicator that supports the decision of the best minimum e-flow strategy to implement in the basin (Eq. 9).

$$\begin{gathered} F = \alpha IHA_g + \beta HabAI_g + \gamma R_{AD} + \delta R_{UD} \\ \alpha + \beta + \gamma + \delta = 1 \end{gathered} \tag{9}$$

where: IHA_g: General indicator of hydrological alteration, $HabAI_g$: General indicator of habitat alteration, R_{AD}: Indicator of agricultural water supply reliability, R_{UD}: Indicator of urban water supply reliability, and α, β, γ and δ: Weighting factors for each indicator.

To properly use the different indicators in the decision-making function (Eq. 9), it was necessary to normalize its different elements within a range of 0 to 1. The normalization of hydrological alteration indicators ($HAI_{g,i}$) is detailed in Section 2.2.1. For the habitat alteration indicators ($HabAI_{g,i}$), their normalization was carried out after calculating the habitat alteration indicator for each river section to get an indicator value ($HabAI^{*}_{g,1}$) between 0 and 1. The agricultural and urban water supply reliability indicators were normalized as detailed in Section 2.4. After the normalization, the general alteration indicators were obtained based on their values in the different river sections (Eqs. 10 and 11).

$$IHA_g = \frac{1}{N}\sum_{i=1}^{N} IHA_{g,i} \tag{10}$$

$$HabAI_g = \frac{1}{N}\sum_{i=1}^{N} HabAI^{*}_{g,i} \tag{11}$$

where N is the number of river sections.

Water supply reliability requires the satisfaction of three criteria for agricultural water demands (annual, bi-annual and decadal) and two criteria for urban water demands (monthly and decadal). This implies that the general indicator of agricultural and urban water supply reliability was considered as the minimum of these criteria (Eqs. 12 and 13, respectively).

$$R_{AD} = Min\left(R_{AD,1year}, R_{AD,2\ years}, R_{AD,10years}\right) \tag{12}$$

where:

$$R_{AD,1\ year} = \frac{1}{N}\sum_{i=1}^{N} R_{AD,1\ year,i}$$

$$R_{AD,2\ years} = \frac{1}{N}\sum_{i=1}^{N} R_{AD,2\ year,i}$$

$$R_{AD,10\ years} = \frac{1}{N}\sum_{i=1}^{N} R_{AD,10\ years,i}$$

N = number of agricultural demand units.

$$R_{UD} = Min\left(R_{UD,1\ month}, R_{UD,10\ years}\right) \tag{13}$$

where:

$$R_{UD,1\ month} = \frac{1}{N}\sum_{i=1}^{N} R_{UD,1\ month,i}$$

$$R_{UD,10\ years} = \frac{1}{N}\sum_{i=1}^{N} R_{UD,10\ years,i}$$

N = number of urban demand units.

The basin management indicator was calculated for seven minimum e-flow scenarios (Section 2.1.2) and four management approaches (Table 4). The four management approaches depend on the attribution of weighting coefficients for the different elements constituting the decision-making function. The first approach consists in considering that all the indicators are of equal importance (α = β = γ = δ = 0.25). The second approach assumes that the urban water supply reliability is twice as important as the other indicators (α = β = γ = 0.2 and δ = 0.4). The third approach considers that the urban water supply reliability is the most important indicator (δ = 0.4), followed by the habitat alteration (β = 0.3), the agricultural water supply reliability (γ =0.2), and the hydrological alteration (α = 0.1). Finally, the fourth approach supposes that urban water supply is the most important element in the calculation of the basin management indicator (δ = 0.4), followed by hydrological alteration (α = 0.3), agricultural water supply reliability (γ =0.2), and habitat alteration (β = 0.1).

Once the basin management indicator was calculated for the different minimum e-flow scenarios and management approaches mentioned above, a comparison was carried out to explore the balance between the environmental concerns, and the urban and agricultural water supplies.

3. Application to a case study

3.1. Study area

The Júcar River Basin is a highly regulated system located in the central-eastern part of the Iberian Peninsula, in Spain. It covers a total area of 22,261 km^2 drained by the Júcar River that flows into the Mediterranean Sea (Fig. 2). The basin is subjected to an irregular Mediterranean climate marked by semi-arid conditions and low rainfall associated with hot summers and mild winters. Mean annual precipitation is around 500 mm and varies from 300 mm in dry years to about 800 mm in wet years. Precipitation in autumn accounts for about 40% of the annual precipitation (CHJ, 2022).

In this work, the SIMGES water allocation model was implemented based on the conceptual model shown in Fig. 3. It includes the main regulation reservoirs (Alarcón, Contreras and Tous), the Sueca-Cullera weir, and other significant reservoirs for hydroelectric production, such as the Cortes, El Naranjero, and La Muela reservoirs. The Cofrentes nuclear power plant is also an essential component of the basin, requiring water to cover its cooling needs.

This model was developed to define the system's behavior while determining its different input and output parameters. Four river sections were chosen to apply the methodology described above: Júcar River downstream Alarcón, Cabriel River downstream Contreras, Júcar River downstream Tous, and Júcar River upstream Sueca-Cullera weir (Figs. 2 and 3). The selection of these river sections was based on the importance that they represent in the basin, their different locations in the basin, and the availability of habitat data. To conduct this work, the model was implemented based on the data of the Júcar Hydrological Plan for the period 2022–2027 (CHJ, 2022).

Table 4
Weighting factors associated to IHA$_g$ (α), HabAI$_g$ (β), R$_{AD}$ (γ) and R$_{UD}$ (δ).

	A	β	γ	δ
Approach 1	0.25	0.25	0.25	0.25
Approach 2	0.2	0.2	0.2	0.4
Approach 3	0.1	0.3	0.2	0.4
Approach 4	0.3	0.1	0.2	0.4

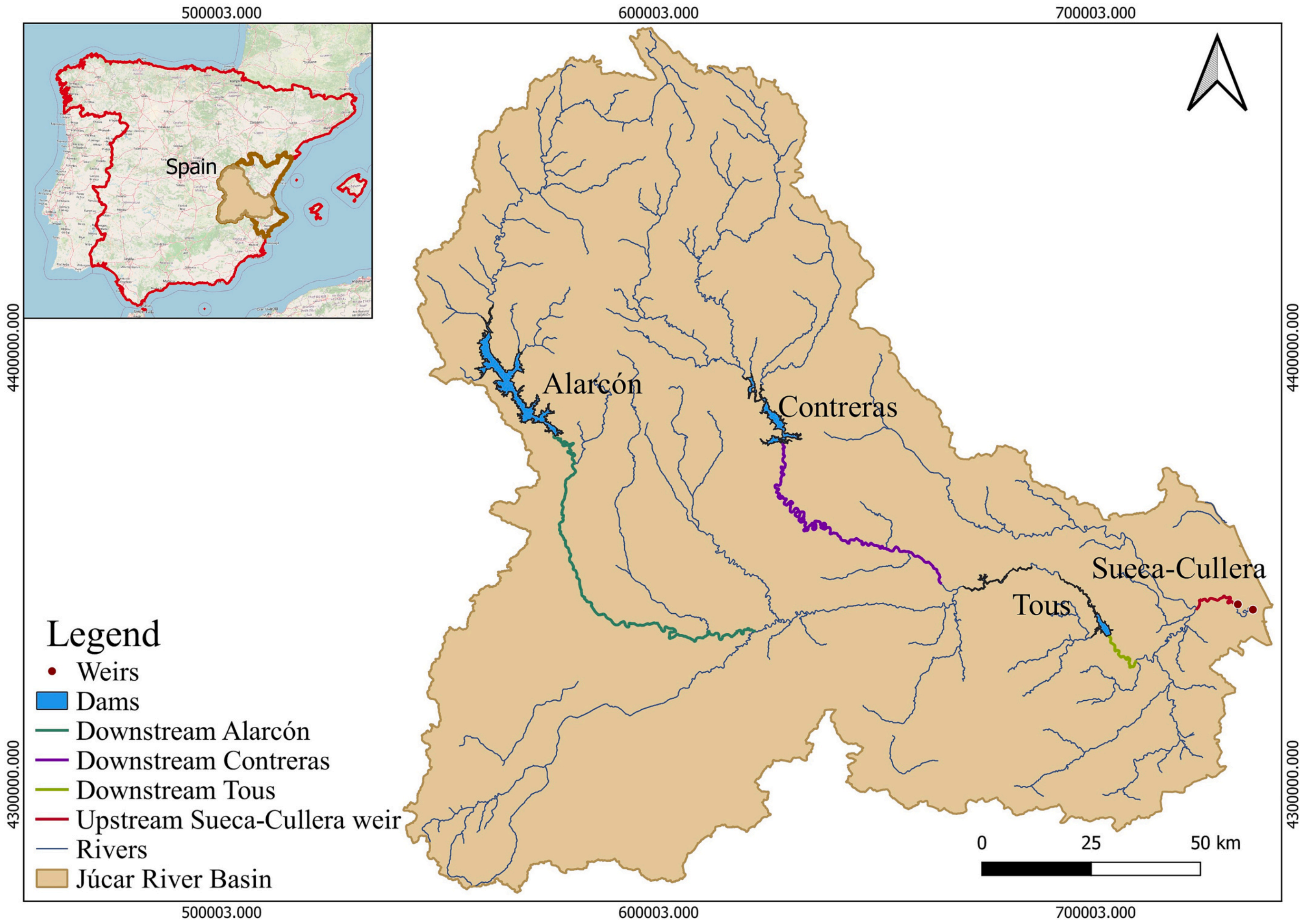

Fig. 2. Location of the Júcar River Basin (eastern Spain).

3.2. Assessment of hydrological alteration

The grouped indicators of hydrological alteration were calculated for each of the four river sections aforementioned. The approach entailed calculating the mean weighted average of the indicators within each group and assigning equal weights to all of them. The results of the five $\mathrm{GIHA_J}$ for the four river sections are presented in Fig. 4.

Analyzing the magnitude of monthly winter and summer hydrological conditions -indicators GIHA1 and GIHA2- is essential to understand the hydrological state of each season. It is also important for deciding about the availability of habitat for aquatic organisms, the availability of water, the reliability of water supply, and the influence on oxygen levels and photosynthesis in the water column (Marcarelli et al., 2010; Richter et al., 1996). The tendency for these two sets of indicators shows that the sections with the most significant alterations are those located downstream of the basin (downstream Tous and upstream Sueca-Cullera weir).

The two indicators representing the magnitude and duration of extreme hydrological conditions (minimum GIHA3, and maximum GIHA4) allow the review of stressful conditions in terms of floods and droughts. They present a significant contribution to the balance between competitive and stress-tolerant organisms, the duration of stressful conditions, such as low oxygen levels and concentrated chemical concentrations in the aquatic environment, as well as the natural turnover of the ecosystem (*The Nature Conservancy*, 2009). GIHA3 and GIHA4 generally show strong alterations for the downstream river sections of the basin (Fig. 4), which are related to the high regulation within the basin showing the current shift in relation to the natural regime.

The remaining GIHA5 group represents the frequency and duration of pulses and changes in hydrological conditions. It is used to assess soil water stress in plants, nutrient and organic material exchange between the river and floodplains, the influence of bed load transport on the channel and duration of substrate disturbance, and desiccation stress on low-mobility organisms (Richter et al., 1996; *The Nature Conservancy*, 2009). The trend of this indicator is the opposite of the other clusters, where the upstream river sections of the basin register the highest alteration.

Fig. 5 illustrates the general indicators of hydrological alteration for each river section. These general indicators were calculated considering that all the $\mathrm{GIHA_J}$ have the same order of priority in the basin (same weighting factor). The indicators are generally in the ranges of the altered and moderately altered status (Table 3). The alteration intensifies from the upstream river sections towards downstream. The river section that represents the most favorable alteration value (lowest alteration) is the one downstream of the Alarcón dam, representing a moderate alteration, whereas the section upstream of the Sueca-Cullera weir represents the most altered section, registering a value of 0.27 and classified as an altered situation. The main reason for this trend is that the downstream sections of the basin depend on the upstream parts, which are strongly regulated by the largest dams in the basin. The hydrological alteration situation in the Júcar River Basin is, therefore, less altered in the upper part of the basin than in the downstream sections.

3.3. Assessment of habitat alteration

The habitat alteration indicators were calculated for the majority of

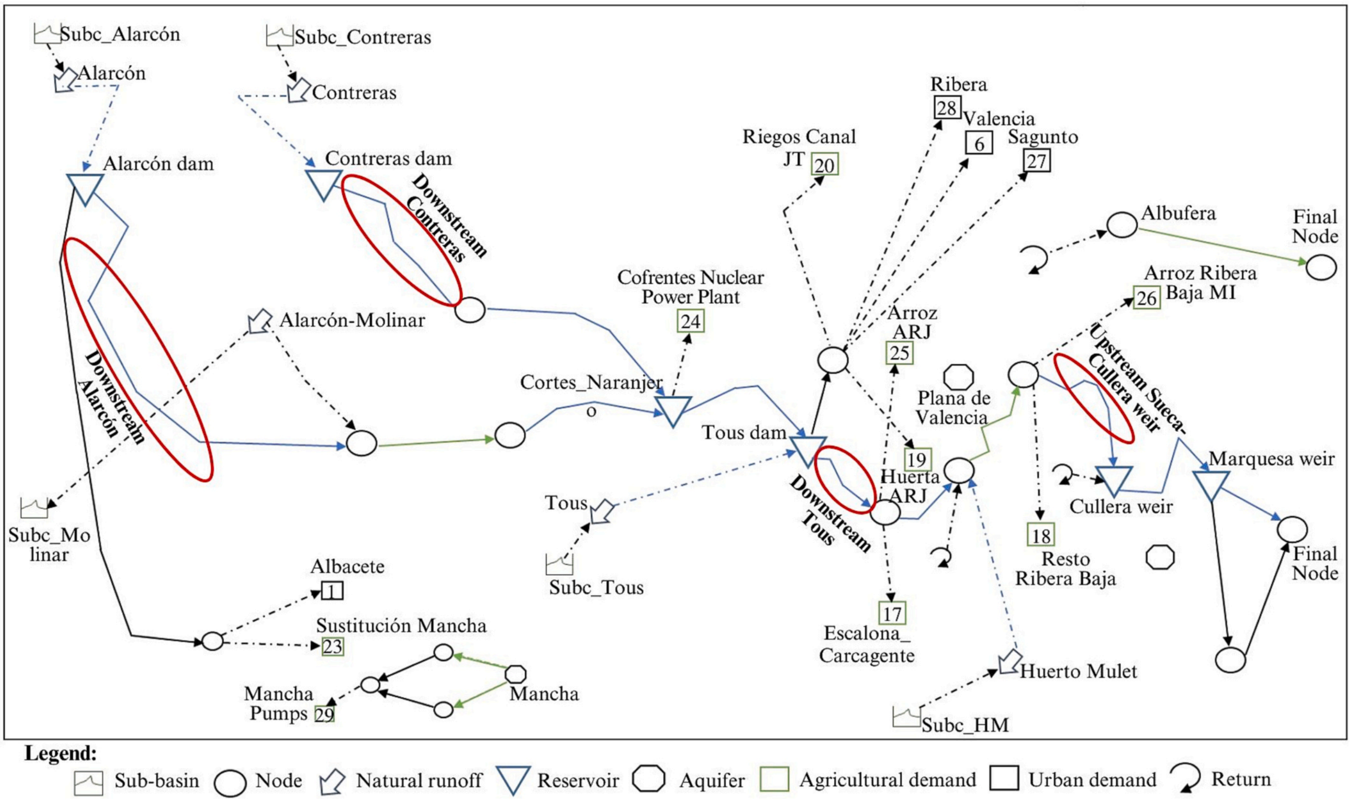

Fig. 3. Topology of the model generated in SIMGES.

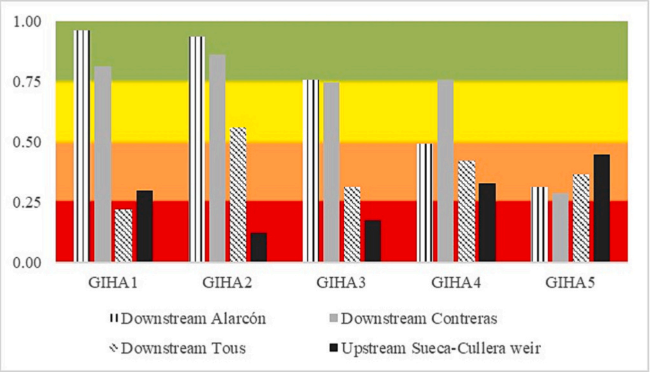

Fig. 4. Indicators of hydrological alteration and classification in four levels of alteration (in colors) in the four river sections.

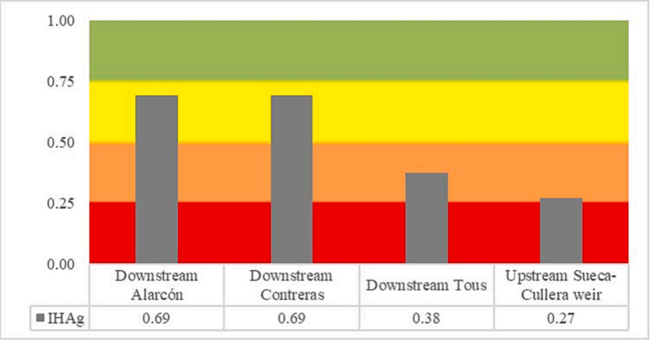

Fig. 5. General indicators of hydrological alteration.

the fish species present in each of the river sections, separated in two groups: the native brown trout (*Salmo trutta* L.) and, on the other hand, the rest of fish species, which belongs to the Cyprinidae family, i.e., Eastern Iberian barbel (*Luciobarbus guiraonis*), chub (*Squalius pyrenaicus and Squalius valentinus*), and Júcar nase (*Parachondrostoma Arrigonis*). This ecological information was generated in different scientific studies previous to the habitat modeling of this work (e.g., Martínez-Capel et al., 2009, 2011; Muñoz-Mas et al., 2012). The Júcar nase is considered as critically endangered fish species, and the Eastern Iberian chub or Valencia chub is vulnerable according to the IUCN (2022). Table 5 shows the bioperiods of these species provided by the Júcar River Basin Agency and the scientific studies aforementioned.

The HTS were obtained for each of the fish species and size classes, under natural and altered regimes, in each river section. Based on these HTS, the corresponding indicators of habitat alteration were calculated. Table 6 lists the different indicators of habitat alteration for each species in each river section, as well as the general indicator by river section.

Downstream of the Alarcón dam, the river presents three species: brown trout, Eastern Iberian barbel, and chub. In this section, the indicator shows values either equal to or slightly greater than one, which indicates a very similar habitat situation in the altered flow regime as in the natural regime. Downstream of the Contreras dam, we find the river section featuring the highest number of species: brown trout, Eastern Iberian barbel, chub, and Júcar nase. The habitat alteration indicator for the Júcar nase is slightly lower than one. This reflects a slight deterioration of the habitat conditions for these two species, while the other species have recorded a slight improvement.

Downstream the Tous dam, the river section shows the smaller aggregated alteration in comparison with the other three altered sections; this is inhabited by three species: Eastern Iberian barbel, chub, and Júcar nase. The habitat situation for this barbel has improved by more than 1.5 compared to the natural regime, considering the entire hydrological year. The river section upstream of the Sueca-Cullera weir is the most altered in terms of habitat; this section includes the Eastern

Table 5

Biologically significant periods for the native fish species in two groups, brown trout and Cyprinid fish species.

	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Brown trout, fry	0	0	0	0	0	1	1	1	1	0	0	0
Brown trout, juvenile	0	0	0	0	0	0	1	1	1	1	1	1
Brown trout, adult	1	1	1	1	1	1	1	1	1	1	1	1
Brown trout, spawning	0	0	1	1	1	1	0	0	0	0	0	0
Cyprinids, fry	1	0	0	0	0	0	0	0	1	1	1	1
Cyprinids, juvenile	0	1	1	1	1	1	1	1	0	0	0	0
Cyprinids, adult	1	1	1	1	1	1	1	1	1	1	1	1

Table 6

Indicators of habitat alteration, aggregated by river section.

	Downstream Alarcón	Downstream Contreras	Downstream Tous	Upstream Sueca-Cullera weir
$\mathrm{GHabAI}_{\mathrm{Brown\ Trout}}$	1	1.03		
$\mathrm{GHabAI}_{\mathrm{Eastern\ Iberian\ Barbel}}$	1	1.03	1.62	0.58
$\mathrm{GHabAI}_{\mathrm{Chub}}$	1.02	1.04	1.45	0.83
$\mathrm{GHabAI}_{\mathrm{Jucar\ Nase}}$		0.99	1.22	0.56
$\mathbf{HabAI}_{\mathbf{g,i}}$	**1.01**	**1.02**	**1.43**	**0.66**

Iberian barbel, chub, and Júcar nase. The indicators of habitat alteration by species entitle them to a reasonable situation, assuming a habitat deterioration compared to the natural regime with the general consideration of all the size classes and all the time periods aggregated.

Each river section's general indicator of habitat alteration (Table 6) shows a range between reasonable and improved conditions. The minimum e-flows lead to the general improvement of the habitat situation in three out of four river sections. Downstream the Tous dam, that indicator is 1.43, representing the best situation in terms of habitat alteration in the basin. The river sections in the upstream river reaches (downstream Alarcón and downstream Contreras) also display a slight habitat improvement. However, for the river reach upstream the Sueca-Cullera weir, the general habitat alteration indicator is lower than one (0.66), representing a negative habitat alteration compared to natural flow conditions.

3.4. *Assessment of water supply reliability*

Table 7 shows the maximum annual, biannual and decadal deficit for the agricultural demand units (ADUs) in the Júcar River Basin for the current minimum e-flow scenario. The green color corresponds to fulfilling the water supply criteria, while the red represents a lack of fulfillment. Most of these units meet the water supply reliability criteria detailed in Section 2.4, except for the unit of *Sustitucion Mancha* (ADU 23) and the *Riegos Canal Júcar-Turia* (ADU 20). In addition, ADU 23 does not meet the annual, biannual and decadal deficit criteria, and ADU 20 does not meet the decadal deficit criteria.

None of the urban demand units in the Júcar River Basin display any deficit in terms of monthly and decadal criteria, i.e., they meet the water supply reliability criteria for urban demands in the current minimum e-flow scenario.

3.5. *Joint assessment for different minimum e-flow scenarios and management approaches*

The seven minimum e-flow scenarios were jointly evaluated for the four river sections analyzed, considering hydrological alteration, habitat alteration and water supply reliability. Fig. 6 represents the hydrological alteration (IHAg) for the different scenarios of minimum e-flows. It is clear that the hydrological alteration is less intense for higher minimum

Table 7

Maximum annual, biannual, and decadal water supply deficits for the nine agricultural demand units (indicated in Fig. 2).

ADU	Annual (%)	Biannual (%)	Decadal (%)
17	26.45	51.45	95.76
18	25	50	94.73
19	26.11	52.17	98.2
20	45.76	90.76	179.82
23	90.38	170.5	322.21
24	0	0	0
25	26.71	52.97	101.54
26	25	50	96.93
29	15	30	62.28

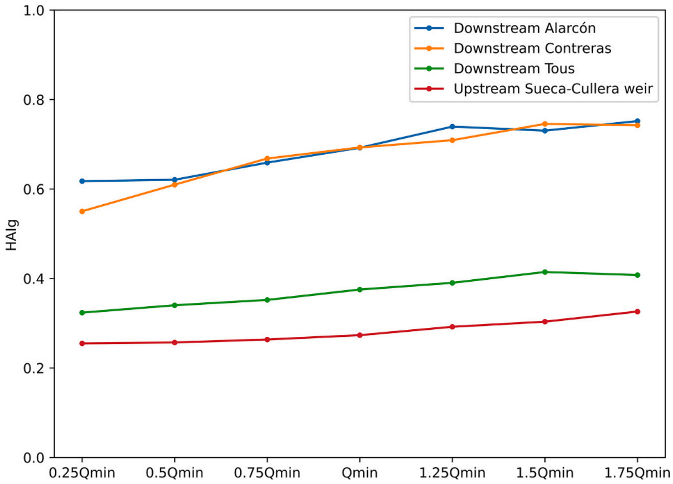

Fig. 6. Values of the general indicator of hydrological alteration in the four analyzed river reaches, under seven minimum e-flow scenarios. Q_{min} represents the current minimum e-flows established in the river basin management plan of the Júcar River Basin District.

e-flows and vice versa. For instance, in the river section downstream of the Alarcón dam, the indicator ranges between 0.62 and 0.75 for the 0.25Qmin and the 1.75Qmin scenarios, respectively. However, for the river reach upstream of the Sueca-Cullera weir, which is located downstream of the other three reaches, the hydrological alteration is more intense, with the same indicator ranging between 0.25 and 0.33 for the 0.25Qmin and 1.75Qmin scenarios, respectively. Compared to the current minimum e-flow scenario, the 1.75Qmin scenario seems to be the best scenario to minimize the hydrological alteration in the different river sections.

The normalization of the habitat alteration indicators allowed us to define habitat alteration values between 0 and 1, which provides the same qualitative classification as for the hydrological alteration (Fig. 7). Among the upstream river sections of the basin, it is noted that for the different minimum e-flow scenarios, downstream Alarcón presents habitat alteration indicators between 0.70 and 0.71, and downstream Contreras presents values between 0.68 and 0.69, classifying them as moderately altered. Downstream Tous is the river section that presents the smallest habitat alteration in the different scenarios. The river reach upstream the Sueca-Cullera weir shows the worst situation, with values between 0.41 and 0.51 for the 0.25Qmin and 1.75Qmin scenarios, respectively.

The indicators of agricultural water supply reliability generally present values that reveal slightly altered situations for the annual criteria. For the biannual criteria almost all ADUs present a slightly altered situation except for ADU20, which has a moderately altered situation for the scenario 1.75Qmin, and ADU23, which shows a moderately altered situation for the seven minimum e-flow scenarios (Fig. 8). The decadal criterion is the one that records more alteration. In fact, the alteration occurs in all ADUs except for ADU24 and ADU29. ADU 23 (*Sustitucion Mancha*) is the most unreliable agricultural unit in terms of water supply.

Concerning the urban demands, the UDUs number 6, 27 and 28 fulfill the decadal urban water supply criteria for all the minimum e-flows (Fig. 9), and the monthly criteria for all the minimum e-flow scenarios except 1.75Qmin. On the other hand, the UDU 1 (Albacete) fulfills the monthly criteria but does not fulfill the decadal criteria for the1.5Qmin and 1.75Qmin scenarios (Fig. 9).

The comparison of the minimum flow scenarios in terms of hydrological alteration and habitat alteration shows that some scenarios improve more the hydrological alteration indicators while others operate better on the habitat alteration by promoting the generation of more habitat (Fig. 10). As the minimum e-flows increase, hydrological and habitat alteration indicators improve, while the urban and agricultural water supply reliability acts in the opposite way.

At this point, the proposed basin management indicator (Eq. 9) is involved, allowing the integration of the different indicators analyzed to obtain a general view of the socio-economic and environmental effects of minimum e-flows. Four management approaches were considered (Table 4) for the seven minimum e-flow scenarios, resulting in 28 values of the basin management indicator (Fig. 11). For these four approaches, the best minimum e-flow scenario to jointly improve hydrological alteration, habitat alteration, and agricultural and urban water supply reliability is 0.75Qmin (Fig. 11). Therefore, for the four management approaches considered in this work, applying the e-flow scenario 0.75Qmin could be advisable in the Júcar River Basin.

4. Conclusions

In this study, we have proposed a new methodology to jointly quantify the effects of e-flows on hydrological alteration, habitat alteration, and urban and agricultural water supply deficits in regulated river

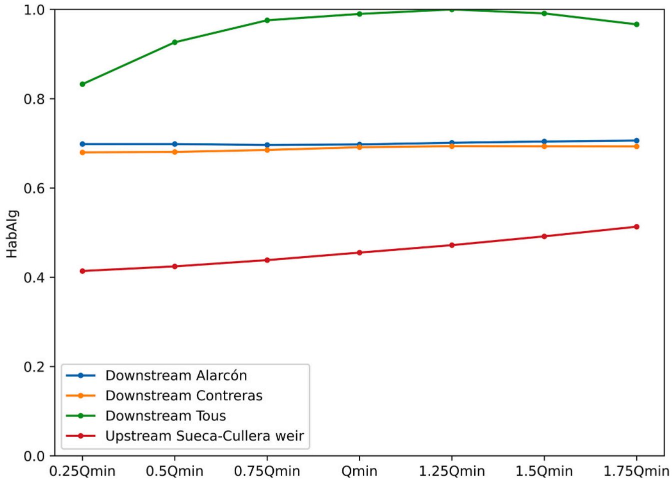

Fig. 7. Values of the general indicator of habitat alteration in the four analyzed river reaches, under seven minimum e-flow scenarios. Q min represents the present minimum flows established in the river basin management plan of the Júcar River Basin District.

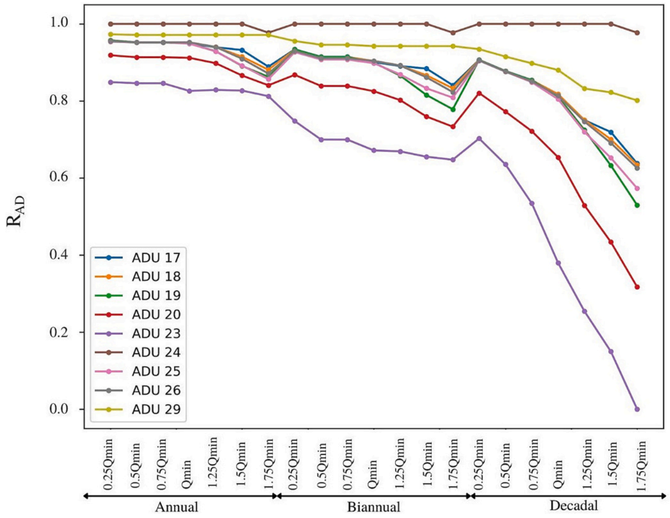

Fig. 8. Values of the indicator of agricultural water supply reliability in the nine Agricultural Demand Units (ADUs) for annual, biannual and decadal criteria, under seven minimum e-flow scenarios.

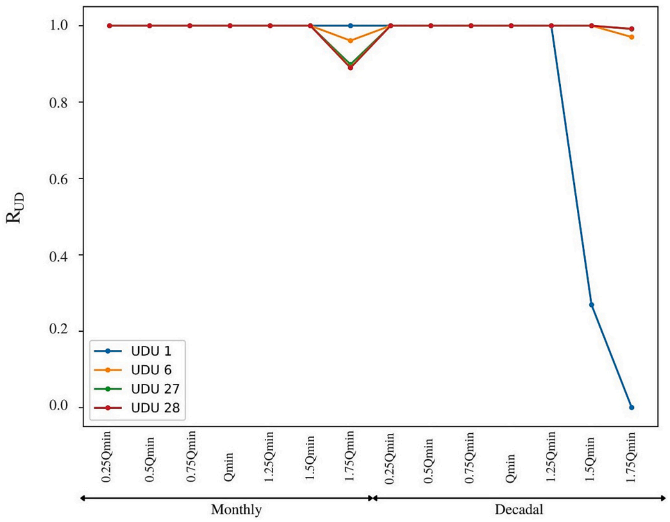

Fig. 9. Values of the urban water supply reliability indicator for monthly and decadal criteria, under seven minimum e-flow scenarios.

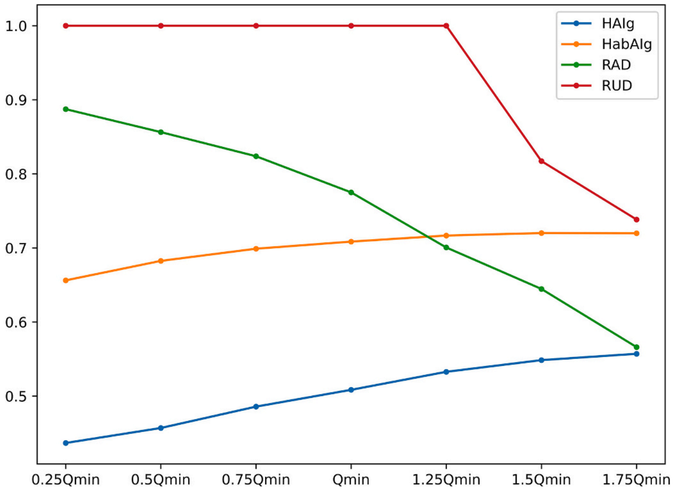

Fig. 10. Variations of the different indicators that define the decision-making function, under seven minimum e-flow scenarios.

basins. The methodology, which is applied to a case study in eastern Spain (the Jucar River Basin), is based on a basin management indicator, which is defined ad-hoc for this work to help identify the best minimum e-flow scenario.

Based on the estimation of the general indicators of hydrological alteration, it was shown that the water bodies with less pronounced alteration are in the upstream part of the basin, while the alteration is more important in the downstream sections. The e-flow scenarios confirm that the higher the minimum flows, the less pronounced the hydrological alteration. Furthermore, the general habitat alteration indicator values generally indicate an improved habitat status (with respect to natural flow conditions) for the upstream river sections of the basin and a worsened state for the downstream river reach. Concerning the water demand, the more the e-flow rate is increased, the more water supply deficit is registered for agricultural and urban demands.

The values of the basin management indicator proposed in this work, which was obtained for seven minimum e-flow scenarios, indicate that the current e-flows do not represent the best scenario to be selected for a joint optimization of hydrological alteration, habitat alteration, and urban and agricultural water supply reliability in the Jucar River Basin. Overall, the results of this work show that the proposed indicators provide a broader vision of the environmental status of the basin and the reliability of water supplies.

The methodology and basin management indicator proposed and applied in this work are extensible to other regulated water resource systems worldwide. In comparison to existing methods, which are mentioned in the introduction section, the methodology proposed in this paper offers distinct advantages for managing e-flows. First, in addition to the IHA, the analysis of habitat alteration enables decision-makers to determine and implement appropriate e-flows that support the maintenance and preservation of diverse ecosystems. Moreover, the inclusion of water demand reliability indicators based on the cumulative deficits over varying periods allows for a more reliable and realistic assessment of water supply failures. The integration of hydrological, habitat, and water demand reliability indicators in the proposed basin management indicator allows a holistic understanding of the interdependencies and trade-offs between environmental flows and various aspects of water resource management. By incorporating these key components, decision-makers can design informed management strategies through the joint evaluation of the effects of e-flows on the environment and the water supplies to demands.

CRediT authorship contribution statement

Syrine Ghannem: Methodology, Software, Investigation, Writing – original draft preparation.

Rafael J. Bergillos: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft preparation, Supervision.

Javier Paredes-Arquiola: Conceptualization, Methodology,

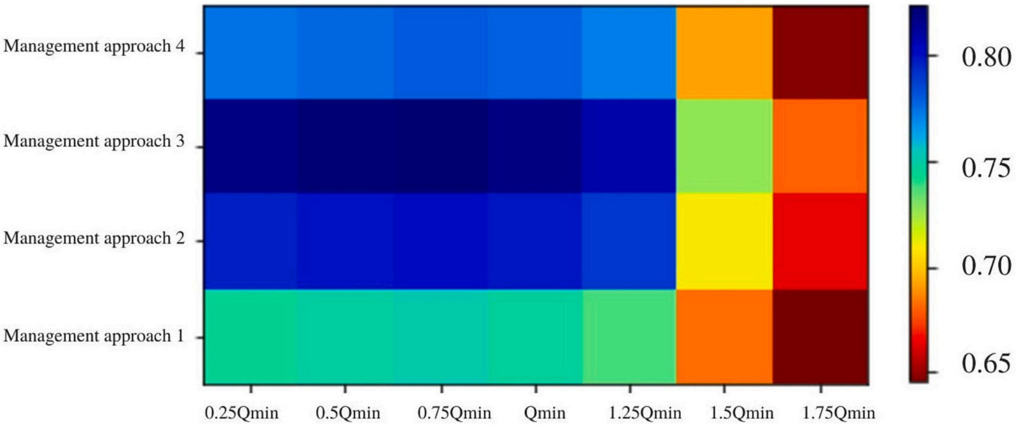

Fig. 11. Values of the basin management indicator for the four management approaches and the seven minimum e-flow scenarios.

Software, Formal analysis, Investigation, Writing – review and editing, Supervision.

Francisco Martínez-Capel: Conceptualization, Formal analysis, Investigation, Writing – review and editing.

Joaquín Andreu: Conceptualization, Writing – review and editing; Project administration, Funding acquisition, Supervision.

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.

Data availability

Data will be made available on request.

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References

Ahn, J.M., Kwon, H.G., Yang, D.S., Kim, Y.S., 2018. Assessing environmental flows of coordinated operation of dams and weirs in the Geum River basin under climate change scenarios. Sci. Total Environ. 643, 912–925.

Alamy Filho, J.E., Paredes-Arquiola, J., Pereira, C.E., De Oliveira, A.L., Salla, M.R., Álvarez, J.A., Solera, A., 2014. Integrated modeling of water quantity and quality in the Araguari River basin, Brazil. Lat. Am. J. Aquat. Res. 42 (1), 224–257.

Al-Jawad, J.Y., Alsaffar, H.M., Bertram, D., Kalin, R.M., 2019. Optimum socio-environmental flows approach for reservoir operation strategy using many-objectives evolutionary optimization algorithm. Sci. Total Environ. 651, 1877–1891.

Andreu, J., Capilla, J., Sanchís, E., 1996. AQUATOOL, a generalized decision-support system for water-resources planning and operational management. J. Hydrol. 177 (3–4), 269–291.

Arévalo-Mejía, R., Leblois, E., Salinas-Tapia, H., Mastachi-Loza, C.A., Bâ, K.M., Díaz-Delgado, C., 2020. A baseline assessment of hydrologic alteration degree for the Mexican catchments at gauged rivers (2016). Sci. Total Environ. 729, 139041.

Arthington, A.H., Bhaduri, A., Bunn, S.E., Jackson, S.E., Tharme, R.E., Tickner, D., Young, B., Acreman, M., Baker, N., Capon, S., Horne, A.C., Kendy, E., McClain, M.E., Poff, N.L.R., Richter, B.D., Ward, S., 2018. The Brisbane declaration and global action agenda on environmental flows (2018). Frontiers in Environmental Science 6, 45.

Behboudian, M., Kerachian, R., Pourmoghim, P., 2021a. Evaluating the long-term resilience of water resources systems: application of a generalized grade-based combination approach. Sci. Total Environ. 786, 147447.

Behboudian, M., Kerachian, R., Motlaghzadeh, K., Ashrafi, S., 2021b. Evaluating water resources management scenarios considering the hierarchical structure of decision-makers and ecosystem services-based criteria. Sci. Total Environ. 751, 141759.

Belmar, O., Velasco, J., Martinez-Capel, F., 2011. Hydrological classification of natural flow regimes to support environmental flow assessments in intensively regulated Mediterranean rivers, Segura River basin (Spain). Environ. Manag. 47, 992–1004.

Bovee, K.D., 1982. A guide to stream habitat analysis using the instream flow incremental methodology. In: Western Energy and Land Use Team, Office of Biological Services, Fish and Wildlife Service, 1. US Department of the Interior.

Bovee, K.D., Lamb, B.L., Bartholow, J.M., Stalnaker, C.B., Taylor, J., 1998. Stream Habitat Analysis Using the Instream Flow Incremental Methodology (United States Geological Survey Biological Resources Division).

Carlisle, D.M., Grantham, T.E., Eng, K., Wolock, D.M., 2017. Biological relevance of streamflow metrics: regional and national perspectives. Freshwater Science 36 (4), 927–940.

CHJ, 2022. Plan Hidrológico de la Demarcación Hidrográfica del Júcar 2022–2027. https://www.chj.es/es-es/medioambiente/planificacionhidrologica/Paginas/PHC-2022-2027-Plan-Hidrologico-cuenca.aspx.

Conesa-García, C., Puig-Mengual, C., Riquelme, A., Tomás, R., Martínez-Capel, F., García-Lorenzo, R., Pastor, J.L., Pérez-Cutillas, P., Martínez-Salvador, A., Cano-Gonzalez, M., 2022. Changes in stream power and morphological adjustments at the event-scale and high spatial resolution along an ephemeral gravel-bed channel. Geomorphology 398, 108053.

De Girolamo, A.M., Barca, E., Leone, M., Porto, A.L., 2022. Impact of long-term climate change on flow regime in a Mediterranean basin. Journal of Hydrology: Regional Studies 41, 101061.

De-Miguel-Gallo, M., Martinez-Capel, F., Muñoz-Mas, R., Aihara, S., Matsuzawa, Y., Fukuda, S., 2019. Habitat evaluation for the endangered fish species Lefua echigonia in the Yagawa River, Japan. Journal of Ecohydraulics 4 (2), 147–157.

Eng, K., Grantham, T.E., Carlisle, D.M., Wolock, D.M., 2017. Predictability and selection of hydrologic metrics in riverine ecohydrology. Freshwater Science 36 (4), 915–926.

Fernández, J.A., Martínez, C., Magdaleno, F., 2012. Application of indicators of hydrologic alterations in the designation of heavily modified water bodies in Spain. Environ. Sci. Pol. 16, 31–43.

Fornaroli, R., Muñoz-Mas, R., Martinez-Capel, F., 2020. Fish community responses to antecedent hydrological conditions based on long-term data in Mediterranean river basins (Iberian Peninsula). Sci. Total Environ. 728, 138052.

Guan, X., Zhang, Y., Meng, Y., Liu, Y., Yan, D., 2021. Study on the theories and methods of ecological flow guarantee rate index under different time scales. Sci. Total Environ. 771, 145378.

Hannah, D.M., Demuth, S., van Lanen, H.A., Looser, U., Prudhomme, C., Rees, G., Stahl, K., Tallaksen, L.M., 2011. Large-scale river flow archives: importance, current status and future needs. Hydrol. Process. 25 (7), 1191–1200.

Hayes, D.S., Brändle, J.M., Seliger, C., Zeiringer, B., Ferreira, T., Schmutz, S., 2018. Advancing towards functional environmental flows for temperate floodplain rivers. Sci. Total Environ. 633, 1089–1104.

He, Y., Lin, K., Zhang, F., Wang, Y., Chen, X., 2018. Coordination degree of the exploitation of water resources and its spatial differences in China. Sci. Total Environ. 644, 1117–1127.

Henriksen, J.A., Heasley, J., Kennen, J.G., Nieswand, S., 2006. Users' Manual for the Hydroecological Integrity Assessment Process Software (Including the New Jersey Assessment Tools). U. S. Geological Survey.

Huang, W., Duan, W., Chen, Y., 2021. Rapidly declining surface and terrestrial water resources in Central Asia driven by socio-economic and climatic changes. Sci. Total Environ. 784, 147193.

IUCN, 2022. The IUCN Red List of Threatened Species.

Joseph, N., Preetha, P.P., Narasimhan, B., 2021. Assessment of environmental flow requirements using a coupled surface water-groundwater model and a flow health tool: a case study of son river in the ganga basin. Ecol. Indic. 121, 107110.

Kapetas, L., Kazakis, N., Voudouris, K., McNicholl, D., 2019. Water allocation and governance in multi-stakeholder environments: insight from Axios Delta, Greece. Science of The Total Environment 695, 133831.

Karr, J.R., Chu, E.W., 2000. Introduction: Sustaining living rivers. In: Assessing the Ecological Integrity of Running Waters. Springer, Dordrecht, pp. 1–14.

Kourgialas, N.N., 2021. A critical review of water resources in Greece: the key role of agricultural adaptation to climate-water effects. Sci. Total Environ. 145857.

Kumar, A.U., Jayakumar, K.V., 2021. Modelling of environmental flow requirements using hydraulic and habitation models. Ecol. Indic. 121, 107046.

Lerma, N., Paredes-Arquiola, J., Andreu, J., Solera, A., Sechi, G.M., 2015. Assessment of evolutionary algorithms for optimal operating rules design in real water resource systems. Environmental Modeling & Software 69, 425–436.

Liang, Y., Cai, Y., Wang, X., Li, C., Liu, Q., 2021. Water security assessment with the improvement of modifying the boundary consistency between footprint and provision. Sci. Total Environ. 801, 149639.

Long, H., Lin, B., Ou, Y., Chen, Q., 2019. Spatio-temporal analysis of driving factors of water resources consumption in China. Sci. Total Environ. 690, 1321–1330.

Marcarelli, A.M., Kirk, R.W.V., Baxter, C.V., 2010. Predicting effects of hydrologic alteration and climate change on ecosystem metabolism in a western US river. Ecol. Appl. 20 (8), 2081–2088.

MARM, 2008. Orden ARM/2656/2008, de 10 de septiembre, por la que se aprueba la Instrucción de Planificación Hidrológica. BOE núm. 229 (22 de septiembre de 2008), 38472–38582.

Martínez-Capel, F., García de Jalón, D., Werenitzky, D., Baeza, D., Rodilla-Alamá, M., 2009. Microhabitat use by three endemic Iberian cyprinids in Mediterranean rivers (Tagus River basin, Spain). Fish. Manag. Ecol. 16 (1), 52–60.

Martínez-Capel, F., Muñoz-Mas, R., Costa, R.M.S., 2011. Estudio comparativo y de transferibilidad de las curvas de preferencia para el establecimiento de caudales ecológicos. In: Technical Report of the Universitat Politècnica de València for the Ministry of Environment and Rural Affairs (Gobierno de España). Valencia, p. 305.

Martínez-Capel, F., García-López, L., Beyer, M., 2017. Integrating hydrological modelling and ecosystem functioning for environmental flows in climate change scenarios in the Zambezi River (Zambezi region, Namibia). River Res. Appl. 33 (2), 258–275.

Miguel, C., Lamouroux, N., Pella, H., Labarthe, B., Flipo, N., Akopian, M., Belliard, J., 2016. Altération d'habitat hydraulique à l'échelle des bassins versants: impacts des prélèvements en nappe du bassin Seine-Normandie. La Houille Blanche 3, 65–74.

Momblanch, A., Paredes-Arquiola, J., Munné, A., Manzano, A., Arnau, J., Andreu, J., 2015. Managing water quality under drought conditions in the Llobregat River Basin. Sci. Total Environ. 503, 300–318.

Monico, V., Solera, A., Bergillos, R.J., Paredes-Arquiola, J., Andreu, J., 2022. Effects of environmental flows on hydrological alteration and reliability of water demands. Sci. Total Environ. 810, 151630.

Monk, W.A., Wood, P.J., Hannah, D.M., Wilson, D.A., 2007. Selection of river flow indices for the assessment of hydroecological change. River Res. Appl. 23 (1), 113–122.

Muñoz-Mas, R., Martínez-Capel, F., Schneider, M., Mouton, A.M., 2012. Assessment of brown trout habitat suitability in the Jucar River basin (SPAIN): comparison of data-driven approaches with fuzzy-logic models and univariate suitability curves. Sci. Total Environ. 440, 123–131.

Muñoz-Mas, R., Marcos-Garcia, P., Lopez-Nicolas, A., Martínez-García, F.J., Pulido-Velazquez, M., Martínez-Capel, F., 2018. Combining literature-based and data-driven fuzzy models to predict brown trout (Salmo trutta L.) spawning habitat degradation induced by climate change. Ecol. Model. 386, 98–114.

Muñoz-Mas, R., Gil-Martínez, E., Oliva-Paterna, F.J., Belda, E.J., Martinez-Capel, F., 2019. Tree-based ensembles unveil the microhabitat suitability for the invasive bleak (Alburnus alburnus L.) and pumpkinseed (Lepomis gibbosus L.): introducing XGBoost to eco-informatics. Ecological Informatics 53, 100974.

Pardo-Loaiza, J., Bergillos, R.J., Solera, A., Paredes-Arquiola, J., Andreu, J., 2022a. Habitat alteration assessment for the management of environmental flows in regulated basins. J. Environ. Manag. 319, 115653.

Pardo-Loaiza, J., Bergillos, R.J., Solera, A., Paredes-Arquiola, J., Andreu, J., 2022b. The role of environmental flows in the spatial variation of the water exploitation index. Water 14 (19), 2938.

Paredes, J., Andreu, J., Solera, A., 2010. A decision support system for water quality issues in the Manzanares River (Madrid, Spain). Sci. Total Environ. 408 (12), 2576–2589.

Paredes-Arquiola, J., Martinez-Capel, F., Solera, A., Aguilella, V., 2013. Implementing environmental flows in complex water resources systems–case study: the Duero river basin, Spain. River Research and Applications 29 (4), 451–468.

Paredes-Arquiola, J., Solera, A., Martinez-Capel, F., Momblanch, A., Andreu, J., 2014. Integrating water management, habitat modelingand water quality at the basin scale and environmental flow assessment: case study of the Tormes River, Spain. Hydrological Sciences Journal 59 (3–4), 878–889.

Pedro-Monzonís, M., Solera, A., Ferrer, J., Andreu, J., Estrela, T., 2016. Water accounting for stressed river basins based on water resources management models. Sci. Total Environ. 565, 181–190.

Peñas, F.J., Barquín, J., 2019. Assessment of large-scale patterns of hydrological alteration caused by dams. J. Hydrol. 572, 706–718.

Poff, N.L., Matthews, J.H., 2013. Environmental flows in the Anthropocence: past progress and future prospects. Curr. Opin. Environ. Sustain. 5 (6), 667–675.

Poff, N.L., David Allan, J., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The Natural Flow Regime 47 (11), 769–784.

Qian, S.S., Kennen, J.G., May, J., Freeman, M.C., Cuffney, T.F., 2021. Evaluating the impact of watershed development and climate change on stream ecosystems: a Bayesian network modeling approach. Water Res. 205, 117685.

Reiser, D.W., Hilgert, P.J., 2018. A practitioner's perspective on the continuing technical merits of PHABSIM. Fisheries 43 (6), 278–283.

Richter, B., Baumgartner, J., Wigington, R., Braun, D., 1997. How much water does a river need? Freshw. Biol. 37 (1), 231–249.

Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A method for assessing hydrologic alteration within ecosystems. Conserv. Biol. 10 (4), 1163–1174.

Song, F., Su, F., Mi, C., Sun, D., 2021. Analysis of driving forces on wetland ecosystem services value change: a case in Northeast China. Sci. Total Environ. 751, 141778.

Tharme, R.E., 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Res. Appl. 19 (5–6), 397–441.

The Nature Conservancy. In: Indicators of Hydrologic Alteration, 2009.

Van Niekerk, L., Taljaard, S., Adams, J.B., Lamberth, S.J., Huizinga, P., Turpie, J.K., Wooldridge, T.H., 2019. An environmental flow determination method for integrating multiple-scale ecohydrological and complex ecosystem processes in estuaries. Sci. Total Environ. 656, 482–494.

Wang, X., Dong, Z., Sušnik, J., 2023. System dynamics modelling to simulate regional water-energy-food nexus combined with the society-economy-environment system in Hunan Province, China. Science of The Total Environment 863, 160993.

Xie, X.J., Lian, Y., Lin, K., Gao, X., Lan, T., Luo, J., Song, F., 2022. Cloud model combined with multiple weighting methods to evaluate hydrological alteration and its contributing factors. J. Hydrol. 610, 127794.