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Effects of environmental flows on hydrological alteration and reliability of water demands

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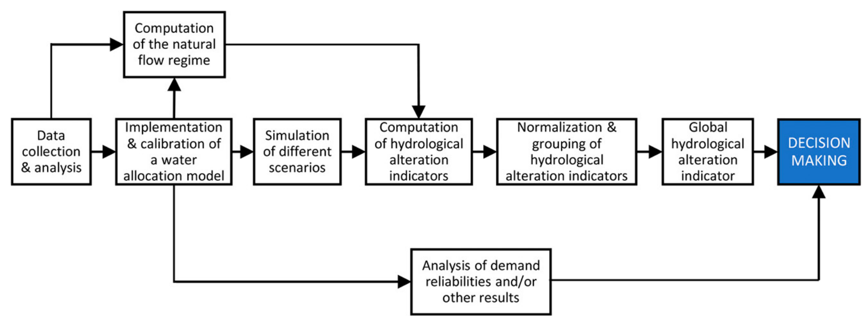
HIGHLIGHTS

- Methodology to quantify the effects of environmental flows on hydrological alteration
- Application of a calibrated water allocation model in the Orbigo River basin (Spain)
- Estimation, normalization, and aggregation of hydrological alteration indicators
- Assessment of effects of environmental flow scenarios on water demand reliabilities
- Helpful tool to design management strategies of environmental flow regimes

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a methodology to assess the effects of management strategies of environmental flows on the hydrological alteration of river basins on a daily scale. It comprises the collection and analysis of data, the implementation and calibration of a water allocation model; the computation of the natural flow regime; and the estimation, normalization, and aggregation of hydrological alteration indicators to obtain a global indicator of the hydrological alteration. The methodology was applied to a case study in the Iberian Peninsula: The Orbigo River basin, which belongs to the Duero River basin district. For that, three management scenarios were defined: the current scenario, a scenario without any environmental flow and the scenario with the environmental flows initially projected for the period 2022–2027. These scenarios were modelled with the SIMGES water allocation model, which is calibrated in the study site, and the hydrological alterations in four river stretches with different locations and characteristics were assessed. The implications of each environmental flow scenario on the demand reliabilities were also analysed. The global indicator of hydrological alteration obtained in the projected scenario was greater (better) than those of the other two scenarios, but the reliabilities of the water demands were worse. The methodology proposed in this work can be helpful to design environmental flow regimes considering both the effects on the hydrological alteration and the implication on the water demand reliabilities.

1. Introduction

The exploitation of water resources has historically been an essential factor for the development of humanity (Long et al., 2019; Busico et al., 2021; Kourgialas, 2021). However, in recent decades, this development has resulted in significant effects on the environment (Zhang et al.,

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2019; Behboudian et al., 2021a; McGinn et al., 2021; Song et al., 2021). One of the most important consequences of the exploitation of water resources is the continuous deterioration of river ecosystems (Wen and Théau, 2020; Behboudian et al., 2021b; Huang et al., 2021). Thus, it was necessary to establish limits to these alterations. These limits are represented by the implementation of environmental flows (Poff and Matthews, 2013; Wang et al., 2015; Kapetas et al., 2019).

The first experiences with environmental flows took place in the United States around the 1940s (Tharme, 2003). In the 1970s, they were expanded to other countries (Rodríguez-Gallego et al., 2011). This has led to different definitions and methods to assess environmental 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). Bunn and Arthington (2002) established four hypotheses related to the direct influence that the flow regime has on river ecosystems: (i) the natural flow regime in a river determines the physical nature of the aquatic habitats, which is directly related with the biotic composition of the river; (ii) the aquatic species establish development strategies in direct response to natural flow regimes; (iii) the maintenance of natural patterns of lateral and longitudinal connectivity is essential for the viability of riparian ecosystems; and (iv) the alteration of flow regimes facilitates the establishment of invasive species.

The different species of an ecosystem associated with a water body evolve and adapt to the conditions set by the natural regime of the river. Thus, to establish an appropriate environmental flow regime, it is necessary to characterize the relationships between hydrological processes and the ecological variables involved (Poff et al., 2017; Yang et al., 2021; Zhang et al., 2021). The range of intra and interannual variation of the regime, along with its characteristics of magnitude, seasonality, duration, frequency, and rate of change, are key factors to preserve natural biodiversity and the integrity of aquatic ecosystems (Poff et al., 1997; Puig et al., 2016; Rodríguez-Benlloch, 2019). Therefore, in regulated rivers it is necessary to establish environmental flow regimes capable of reproducing the temporal variability of the river in its natural state (Paredes-Arquiola et al., 2014; Ahn et al., 2018). This allows the reduction of hydrological alteration and, consequently, the maintenance of river ecosystems.

To determine the degree of hydrological alteration of a basin, different methodologies have been proposed (Richter et al., 1996; Richter et al., 1997; Pyron and Neumann, 2008; Lu et al., 2018; do Vasco et al., 2019). These methodologies are based on the comparison of the hydrological regime of the basin in its current state with the hydrological regime under natural conditions (that is, the regime that the system would have if there were no anthropogenic alterations). This comparison is performed by means of a series of hydrological alteration indicators, which allow the classification of the ecological status of the river (Pumo et al., 2018). The main methodologies to determine hydrological alteration are the Indicators of Hydrologic Alteration in Rivers (Martínez Santa-María and Fernández Yuste, 2010) and the Indicators of Hydrologic Alteration (Richter et al., 1996). However, to our best knowledge, these indicators have not been assessed through water allocation models on a daily scale.

The main objective of this work is to establish a methodology that allows assessing the impact of management strategies of environmental flow regimes on the hydrological alteration of the rivers on a daily scale. The methodology is illustrated through a case study in the Iberian Peninsula, where the hydrological alterations of several river stretches are quantified under different management strategies, and the effects of these strategies on the demand reliabilities are also evaluated. The main innovations of the study are: (i) the calculation of hydrological alteration indicators by means of a water allocation model on a daily scale, and (ii) the normalization and aggregation of these indicators to provide a global indicator that evaluates the hydrological status of the rivers.

2. Methodology

The methodology proposed in this work is based on: (i) the collection and analysis of runoff, flow, and reservoir volume data; (ii) the implementation and calibration of a water allocation model; (iii) the computation of the natural flow regime; and (iv) the estimation, normalization, and aggregation of the hydrological alteration indicators (HAIs) to obtain a global indicator of hydrological alteration (Fig. 1).

2.1. Water allocation model

2.1.1. Computation of the natural flow regime

The computation of the natural flow regime is intended to generate flow series that represent the conditions of the basin if the different anthropic interventions had not taken place. To generate these series of flows, different methodologies can be used depending on the conditions of the basin. If there are unaltered river stretches, measurements of flow rates in these stretches could be used directly. Otherwise, a restitution of the series in altered regime to natural regime must be performed. This restitution can be made through a balance of contributions, deductions, returns and derivations. However, these data are often not available, so many times the restitution is performed with a water allocation model.

The contributions under natural regime in the basin allow the evaluation of the alteration in the basin. In this work, the restitution to the natural regime was performed with the water allocation model SIMGES (Andreu et al., 2007), which belongs to the Decision Support System (DSS) AQUATOOL (Andreu et al., 1996). AQUATOOL was designed as a user-friendly interface to support the management and planning of water resources in complex river basins. It has been widely used in the past two decades for research and management purposes (e.g., Paredes et al., 2010; Lerma et al., 2015; Momblanch et al., 2015,

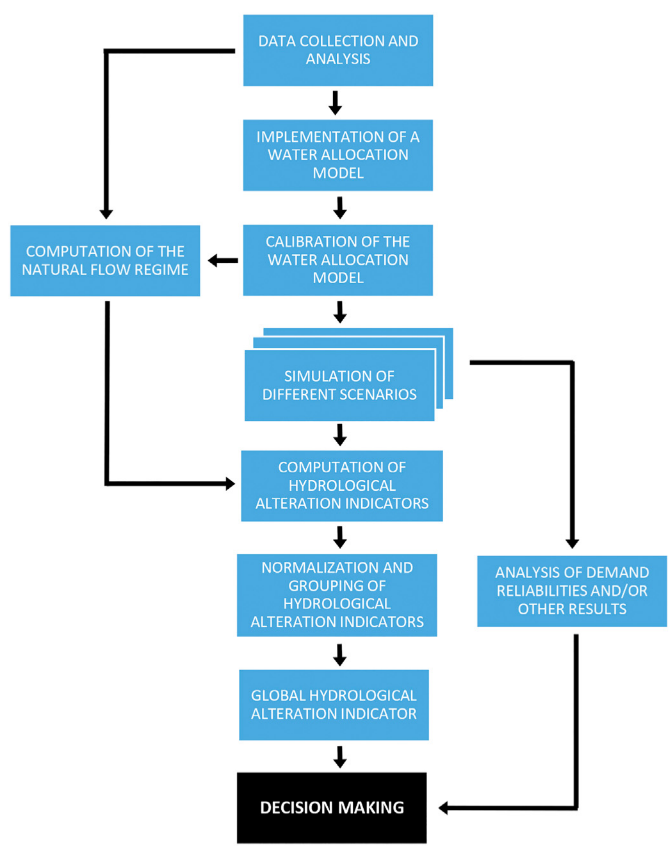

Fig. 1. Flow chart of the methodology proposed to assess the hydrological alteration and demand reliabilities.

2017; Pedro-Monzonís et al., 2016a, 2016b; Haro-Monteagudo et al., 2017). The model was calibrated at the study site for the elaboration of the Hydrological Plan of the basin 2016–2021 (Confederación Hidrográfica del Duero, 2015).

2.1.2. Simulation of management scenarios

The hydrological alteration of different management scenarios can be estimated by means of the natural regime series previously obtained and the application of the calibrated water allocation model in altered conditions. Depending on the management objectives, it could be necessary to analyse and quantify several future scenarios, considering the expected changes in infrastructures, demands, operational rules and/or environmental restrictions, among others. In this work, three management scenarios were considered: the current scenario, a regulated scenario assuming that there are no environmental flows, and a regulated scenario that represents the environmental flows projected in the Hydrological Plan of the basin for the period 2022–2027.

2.2. Hydrological alteration indicators

The use of HAIs is increasingly frequent to support the decision-making process in water planning and management. They relate multiple factors to establish comparative criteria that allow defining the state in which these resources are found. In this work, the 33 indicators proposed by The Nature Conservancy were calculated using the software IHA 7.1 (The Nature Conservancy, 2009). The HAIs evaluated are summarized in Table 1.

2.3. Proposal of grouped and global hydrological alteration indicators to evaluate the hydrological alteration of the river

2.3.1. Normalization and grouping of HAIs

The HAIs were normalized so that all of them adopt values between zero (maximum alteration) and one (no alteration). The normalization performed consisted of the application of the following equations:

Table 1
Hydrological alteration indicators (Richter et al., 1996).

Magnitude of monthly hydrological conditions	Winter	October	HAI1
		November	HAI2
		December	HAI3
		January	HAI4
		February	HAI5
		March	HAI6
	Summer	April	HAI7
		May	HAI8
		June	HAI9
		July	HAI10
		August	HAI11
		September	HAI12
Magnitude and duration of annual extreme hydrological conditions	Low flows	Annual minima, 1-day mean	HAI13
		Annual minima, 3-day mean	HAI14
		Annual minima, 7-day mean	HAI15
		Annual minima, 30-day mean	HAI16
		Annual minima, 90-day mean	HAI17
		Number of zero-flow days	HAI18
		Base flow index	HAI19
	High flows	Annual maxima, 1-day mean	HAI20
		Annual maxima, 3-day mean	HAI21
		Annual maxima, 7-day mean	HAI22
		Annual maxima, 30-day mean	HAI23
		Annual maxima, 90-day mean	HAI24
Timing of annual extreme hydrological conditions		Julian date of annual 1-day minimum	HAI25
		Julian date of annual 1-day maximum	HAI26
Frequency and duration of high and low pulses		Number of low pulses	HAI27
		Duration of low pulses	HAI28
		Number of high pulses	HAI29
		Duration of high pulses	HAI30
Rate and frequency of changes in hydrological conditions		Rise rates	HAI31
		Fall rates	HAI32
		Number of hydrological reversals	HAI33

$$If\ -1 \le HAI \le 0 : HAI_n = HAI + 1 \quad (1)$$

$$If\ HAI > 0 : HAI_n = \frac{1}{1 + HAI} \quad (2)$$

Once the HAIs were normalized, they were classified and grouped in five indicators. The grouping of the $HAIs_n$ is based on the type of variables involved in the evaluation of each indicator. Thus, the first and second grouped $HAIs_n$ represent seasonal indicators of winter and summer months, respectively. The third and fourth grouped $HAIs_n$ include extreme minimum and maximum indicators, respectively. Finally, the fifth grouped HAI_n encompass the indicators related to rates, frequency and duration of pulses and changes in hydrological conditions.

These five indicators are obtained through the weighted average of the indicators considered in each group, that is:

$$GHAI_1 = \sum c_i \cdot HAI_{n,i};\ \sum c_i = 1;\ i = i = 1, 2, 3, 4, 5, 6 \quad (3)$$

$$GHAI_2 = \sum c_i \cdot HAI_{n,i};\ \sum c_i = 1;\ i = 7, 8, 9, 10, 11, 12 \quad (4)$$

$$GHAI_3 = \sum c_i \cdot HAI_{n,i};\ \sum c_i = 1;\ i = 13, 14, 15, 16, 17, 18, 19, 25 \quad (5)$$

$$GHAI_4 = \sum c_i \cdot HAI_{n,i};\ \sum c_i = 1;\ i = 20, 21, 22, 23, 24, 26 \quad (6)$$

$$GHAI_5 = \sum c_i \cdot HAI_{n,i};\ \sum c_i = 1;\ i = 27, 28, 29, 30, 31, 32, 33 \quad (7)$$

where $HAI_{i,n}$ are the hydrological alteration indicators detailed in Table 1 and normalized according to Eqs. (1) or (2), and c_i are the weighting factors. The value of each weighting factor is defined according to the importance of the corresponding HAI_n for the management objectives of the basin. The sum of the weighting factors of each GHAI must be equal to 1.

Finally, a global indicator of hydrological alteration is defined to jointly consider the five GHAIs previously detailed. The global indicator (GI) is, thus, obtained as:

$$GI = K_1 \cdot GHAI_1 + K_2 \cdot GHAI_2 + K_3 \cdot GHAI_3 + K_4 \cdot GHAI_4 + K_5 \cdot GHAI_5 \quad (8)$$

where K_1, K_2, K_3, K_4 and K_5 are the weighting factors of each GHAI. The greater the importance of the $GHAI_i$ for the management objectives of the basin, the greater the value of the corresponding K_i. The sum of the weighting factors must be equal to 1.

2.3.2. Evaluation of the hydrological alteration of the river

The goal of the proposed methodology is to assess the effect of the different management strategies on the hydrological alteration of the river stretches. Therefore, once the results of the GIs are obtained, it is necessary a qualitative assessment to facilitate the interpretation of the results and evaluate the hydrological alteration. In the present work, the four ranges of hydrological alteration shown in Table 2 were proposed.

The relationship between quantitative and qualitative assessment proposed in Table 2 could be modified by the water managers as a function of the basin characteristics or the management objectives, among others.

Table 2
Hydrological status of the basin according to the GI value.

Hydrological status	GI value range
Slightly altered (or not altered)	0.75–1
Moderately altered	0.5–0.75
Altered	0.25–0.5
Very altered	0–0.25

3. Study area

The Orbigo river basin belongs to the Orbigo exploitation system of the Duero Basin Agency and covers an area of 4987 km^2. The Orbigo basin has 26 permanent streams. The Omaña and Luna rivers are located at the head of the exploitation system. They lead into the Orbigo river (Fig. 2). The main tributaries of the Orbigo river are the Tuerto, Jamuz and Eria rivers (Confederación Hidrográfica del Duero, 2015).

There are seven reservoirs in the basin. The reservoir with the greatest importance and capacity is known as Barrios de Luna. The Barrios de Luna reservoir is located at the head of the Luna River and has a capacity of 308 hm^3. Another reservoir in the basin is known as Villameca, is located at the head of the Tuerto river and has a capacity of 20 hm^3. On the other hand, Valdesamario and Selga de Ordas are diversion nodes, and their storage capacity is not very representative. The Valtabuyo, Antoñan del Valle, and Villagaton reservoirs have a local regulatory effect, since they are in rivers that contribute to the irrigation of small communities of irrigators. The Barrios de Luna, Villameca, Villagaton, Valdesamario, Valtabuyo and Antoñan del Valle reservoirs define independent sub-basins, so that each infrastructure regulates the water resources generated within its sub-basin, facilitating the allocation of these resources.

The system also has nine hydroelectric plants that cover an average annual production of 156 GWh. Regarding the demands, in general terms, the Orbigo exploitation system supplies water for the irrigation of 68,400 ha, two fish farms, the supply for 140,000 people and the demands produced by the industry.

Four river streams representative of different characteristics were selected to apply the proposed methodology: Luna, Valdesamario, Tuerto, and Orbigo (Fig. 3). The Luna stretch is in the upper part of the

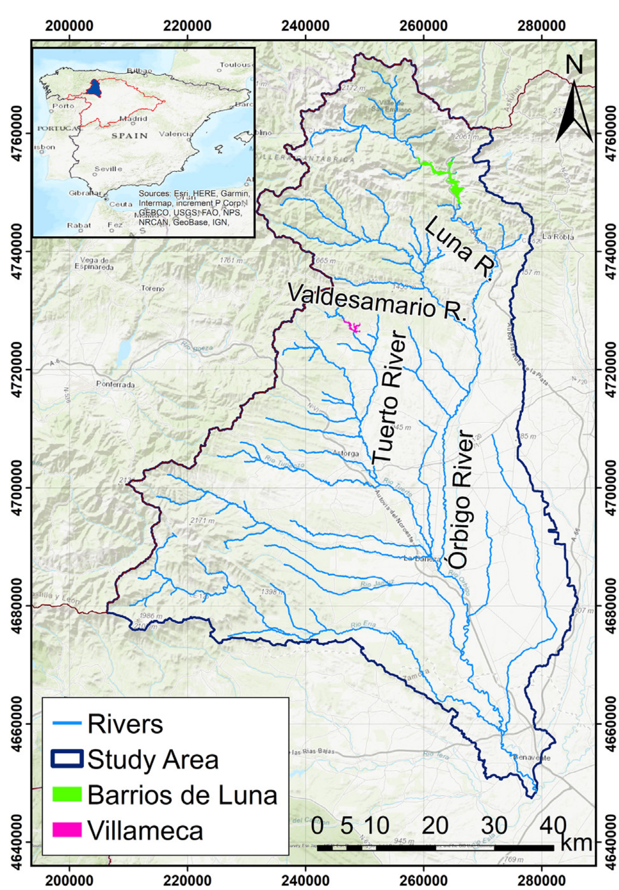

Fig. 2. Location of the study area, the two main reservoirs of the Orbigo River basin, and the four river stretches analysed in this work.

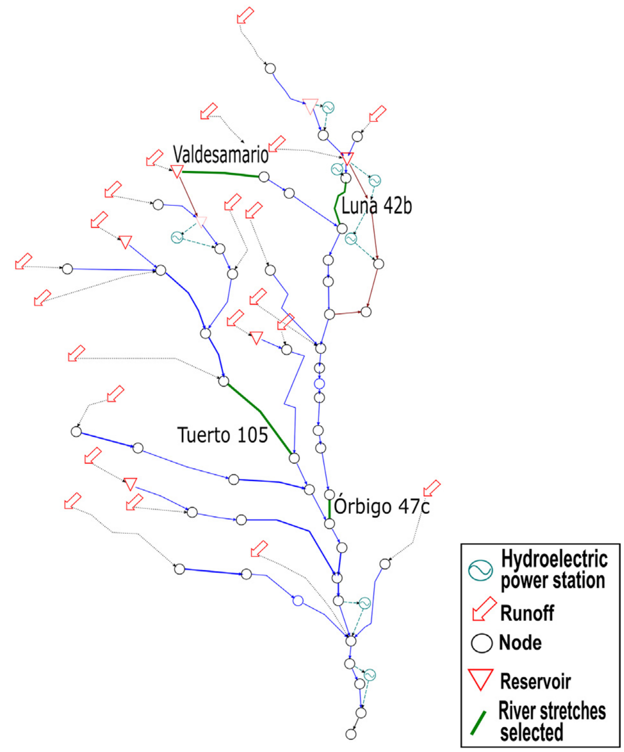

Fig. 3. Topology of the model generated in SIMGES. The river stretches selected for this work are marked in green.

basin, but approximately 40 km downstream from the most important reservoir in the system and very close to two hydroelectric plants. This means that the flow regimes in this stretch are strongly regulated. Valdesamario is located in the upper part of the basin and just downstream of the Villameca reservoir, which is the second most important reservoir in the system. Therefore, this section is representative of the influence of the headwater reservoir and how its impact can be altered with the implementation of a flow regime. Tuerto is in the middle basin and all its tributaries are regulated. Finally, Orbigo represents the lower-middle basin of the Orbigo exploitation system. However, unlike the Tuerto section, some of its tributaries have unregulated contributions.

As mentioned in Section 2.1.1, the SIMGES management model was used for this work. This model was calibrated by the Duero Basin Agency for the elaboration of the Hydrological Plan 2016–2021 (Confederación Hidrográfica del Duero, 2015). To simulate the natural regime, all the elements that represent some type of regulation or alteration in the basin were removed in the SIMGES water allocation model. This implies the elimination of regulation structures (including operating rules and initial volume values), artificial pipelines, demand intakes, and pumps.

In this way, daily flows in natural regime were obtained for all the currents considered in the model. In addition to the natural regime, three simulation scenarios were considered: (i) the current regulation scenario, (ii) a regulated scenario assuming that there are no environmental flows, and (iii) a regulated scenario that represents the environmental flows initially projected for the Orbigo river subbasin in the Hydrological Plan 2022–2027.

4. Results and discussion

4.1. Comparisons of natural and managed flows for the different scenarios

Fig. 4 depicts the boxplots of the river flows in the natural regime and the three regulated scenarios (base, no e-flow and

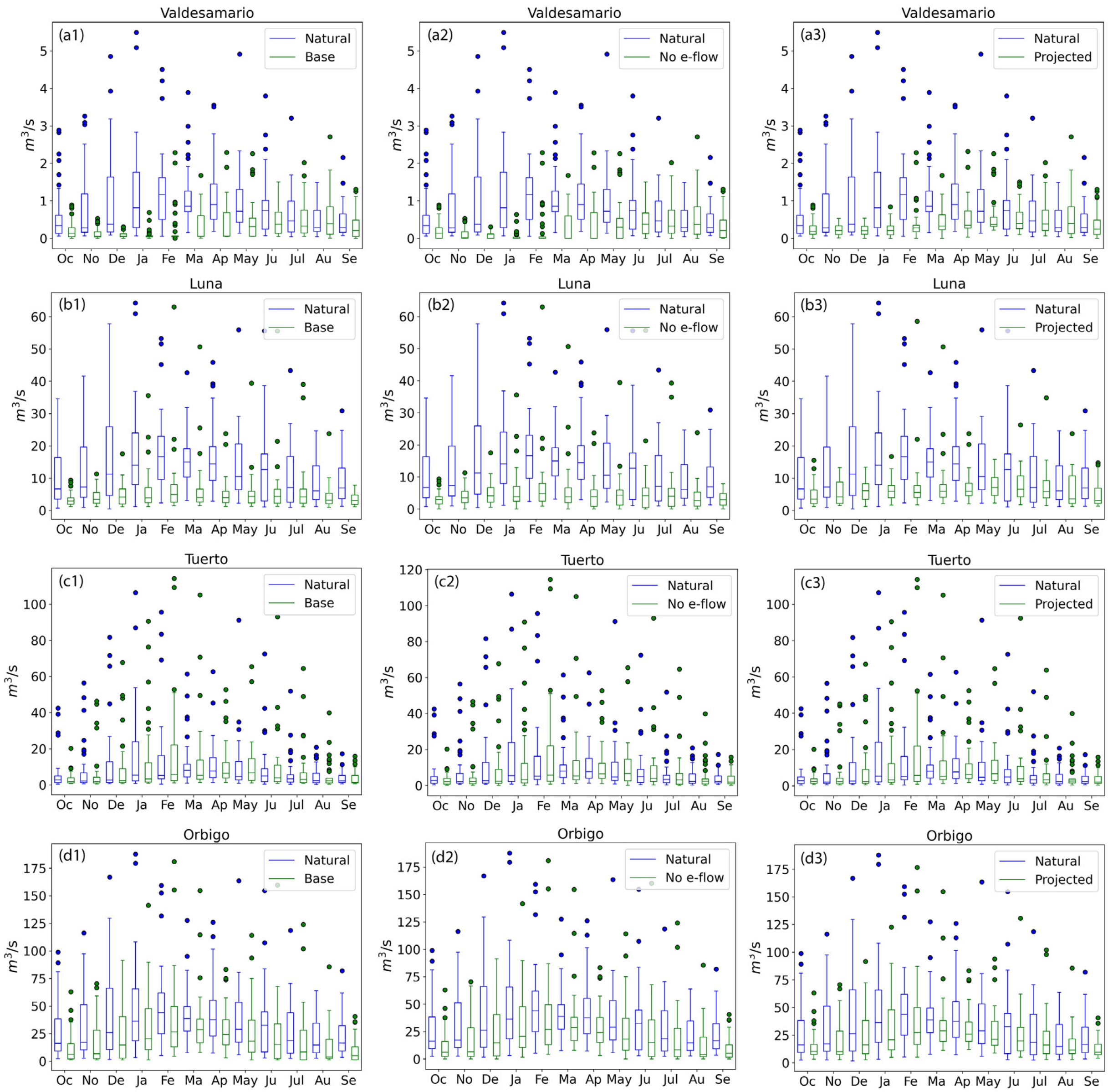

Fig. 4. Boxplots of natural and managed flows in the river stretches Valdesamario (a), Luna (b), Tuerto (c) and Orbigo (d) for the base (1), no-eflow (2) and projected (3) scenarios.

projected) in the four river stretches analysed in this work and marked in green in Fig. 3: Valdesamario, Luna, Tuerto, and Orbigo.

It is observed how the median and percentiles of the flow distributions in the natural regime are greater than those obtained in the three regulated scenarios in the four river stretches. Among the regulated scenarios, the flow percentiles in the projected scenarios are generally greater than those of the base scenario that, in turn, are greater or similar than those of the scenario without environmental flows.

Regarding the mean flows in each scenario and river stretch, Fig. 5 reveals that, again, the natural regime flows are greater than the regulated flows in most of the months. The mean flows in the projected scenarios are equal or greater than those of the other two scenarios in the four river stretches. Finally, the flows of the base scenario are generally greater than those of the no e-flows scenario in the Valdesamario stretch, but similar in the other three river stretches. These trends indicate that the current scenario is almost equivalent to not imposing any environmental flow in the Luna, Tuerto, and Orbigo stretches.

4.2. Computation and comparison of hydrological alteration indicators for the management scenarios

4.2.1. Individual hydrological alteration indicators

The indicators of the magnitude of monthly hydrological conditions (HAI1 to HAI12, Table 1) are related to the availability of habitat, food, and water for the different species within the ecosystem. They are also related to the temperature of the water and the levels of dissolved oxygen in the water body. An important alteration in any of the months can generate adverse conditions for native species and promote the settlement of invasive species.

Considering the seasonal conditions in the Orbigo river basin, the indicators for the winter months (HAI1 to HAI6) and the summer months (HAI7 to HAI12) are analysed separately for each scenario. The results are shown in Fig. 6. As a general trend, the river stretches that present the slightest alterations in these twelve HAIs are Orbigo and Tuerto.

The current environmental flow regime (base scenario) only slightly improves these indicators with respect to the scenario without environmental flows. As can be observed in Fig. 6, the scenario of the projected flows provides monthly HAIs that represents lower alterations than the

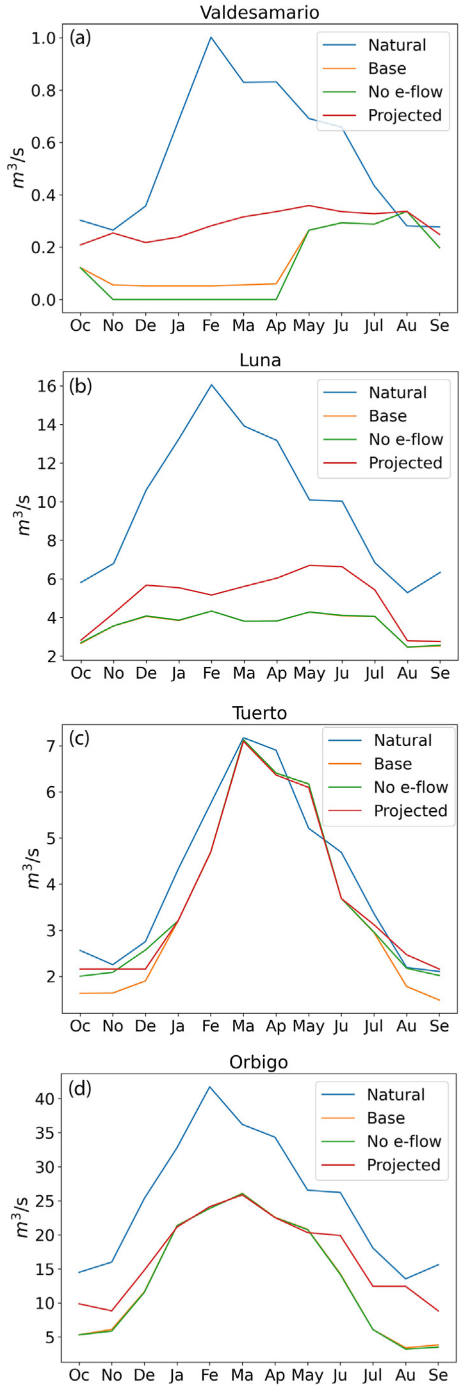

Fig. 5. Mean flows of the natural and regulated scenarios in the river stretches Valdesamario (a), Luna (b), Tuerto (c) and Orbigo (d).

other two scenarios in October, January, June, July, and September (in the stretch Valdesamario); January, February, April, and May (in the stretch Luna); May, June, July, and September (in the stretch Tuerto), and October, December, July, August, and September (in the stretch Orbigo). The greatest improvements with the projected flows compared to the other two scenarios are obtained in the Valdesamario stretch.

Some isolated HAI values are lower (more altered) for the projected scenario than for the other two scenarios. This may be due to the fact that the environmental flow values considered in the projected scenario for these months are slightly higher than the flows in these stretches under natural conditions.

The analysis of extreme hydrological conditions is important due to the relationship that these conditions have in the competition between organisms, the natural renewal of the ecosystem and the capacity of the system to eliminate waste. In this section, the indicators related to low flows and the indicators related to high flows are independently assessed. For low flows, eight indicators are evaluated: annual minimums of the average of one, three, seven, thirty and ninety days, the number of days with zero flow, the base flow index, and the Julian date of annual 1-day minimum (Table 1). For high flows, the annual minimums of the average of one, three, seven, thirty and ninety days, along with the Julian date of annual 1-day maximum, are assessed.

These indicators generally show high alterations, especially for the scenario without environmental flows (Fig. 7). However, in the case of low flows, a significant improvement is evident as the environmental flows considered are higher, which is especially evident in the Luna, Tuerto and Orbigo rivers. Regarding high flows, they present a very similar behaviour in the three scenarios considered. This is a logical trend since the proposed environmental flows do not involve flood flows.

The indicators evaluated in the fourth group are related to the stress that organisms can suffer due to the alteration of the natural hydrological conditions. They are also related to the exchange of nutrients and the accessibility to different feeding sites. Fig. 8 shows the results obtained from the hydrological indicators related to the rate, frequency, and duration of pulses as well as the changes in hydrological conditions. The values of these HAIs indicate that, in general, there are no significant and representative improvements in the hydrological alteration when the flow regime conditions vary from the minimum flow scenarios. The main improvements are obtained for four of the seven analysed HAIs in the Tuerto river, and for the mean duration of low pulses in the Valdesamario stretch (Fig. 8).

4.2.2. Grouped and global hydrological alteration indicators

The HAIs shown in Figs. 6, 7 and 8 were grouped into five indicators by means of Eqs. (3), (4), (5), (6) and (7). This allows the simplification of the information, providing a general view of the status of the basin. In addition, the aggregation of HAIs allows prioritizing the indicators that are more important and representative for the basin management objectives, facilitating the decision-making process related to water planning.

In this work, all the indicators within each group were considered to have the same importance, and therefore the same values were assigned to the weighting factors of each group. The results of each grouped hydrological alteration indicator (GHAI) are shown in Fig. 9. In general terms, it is observed how the projected scenario provides greater (better) GHAIs than those of the other two scenarios. This is in agreement with the results reported in the previous section (Figs. 6, 7 and 8).

The GHAIs that reveal the greatest alteration are those related to the magnitudes and durations of the minimum annual extreme hydrological conditions in Valdesamario and Orbigo (GHAI3), and those related to the magnitudes and durations of the minimum flows in the Luna stretch (GHAI4). On the other hand, the least alteration is obtained for the magnitudes of the monthly summer conditions (GHAI2) in the Valdesamario and Luna stretches, and in the winter months (GHAI1) in Orbigo; whereas the Tuerto River presents the lowest alteration in extreme annual maximum hydrological conditions (GHAI3).

As it is also shown in Fig. 9, the grouped indicators related to the magnitude and duration of annual minimum flows have a greater sensitivity to the variation of the environmental flows considered. The greatest variation is obtained in the Orbigo stretch of river.

Regarding the qualitative evaluation of the state of the river sections, the values of the indicators are generally within the altered and moderately altered ranges, although in the Tuerto river the values within the slightly altered range predominate. The Tuerto and Orbigo river stretches present the most favourable alteration values of the four sections considered. This is due to the locations of these river stretches in

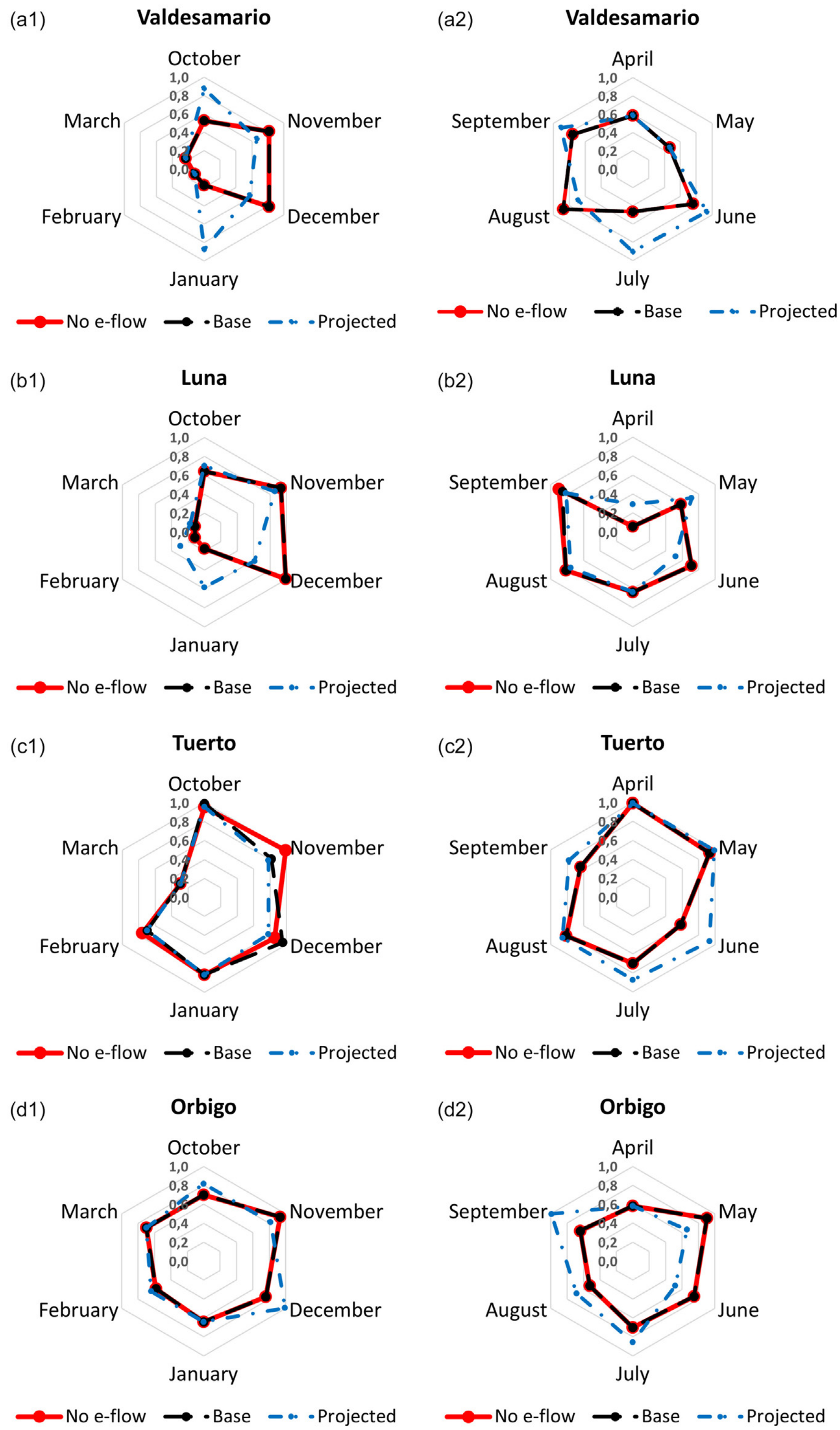

Fig. 6. Hydrological alteration indicators related to the magnitude of monthly hydrological conditions. (a) Valdesamario, (b) Luna, (c) Tuerto, (d) Orbigo. (1) Autumn and winter months, (2) spring and summer months.

the lower-middle part of the basin, so that they receive some returns from the upper part of the basin. In addition, some of the contributions that they receive are not regulated by reservoirs.

On the other hand, in the Valdesamario and Luna River stretches, the GHAIs generally adopt values below 0.5, which are indicative of an altered state. In the projected scenario, the GHAIs present greater values (less alteration), except the GHAI that evaluates the magnitude and duration of the extreme annual hydrological conditions of the high flows in the Luna River stretch.

Finally, to summarize all the HAIs in a single global indicator, the GIs of each section were calculated by means of Eq. (8). In this case, the same weighting factor (same importance) was considered for all the GHAIs. Fig. 10 shows the GIs obtained for each stretch of river and each scenario analysed. These results allow the quantitative and qualitative evaluation of the degrees of alteration of each stretch of river.

Fig. 10 reveals that the most favourable (greatest GI value) are obtained in the Tuerto stretch (with values greater than 0.65 and up to

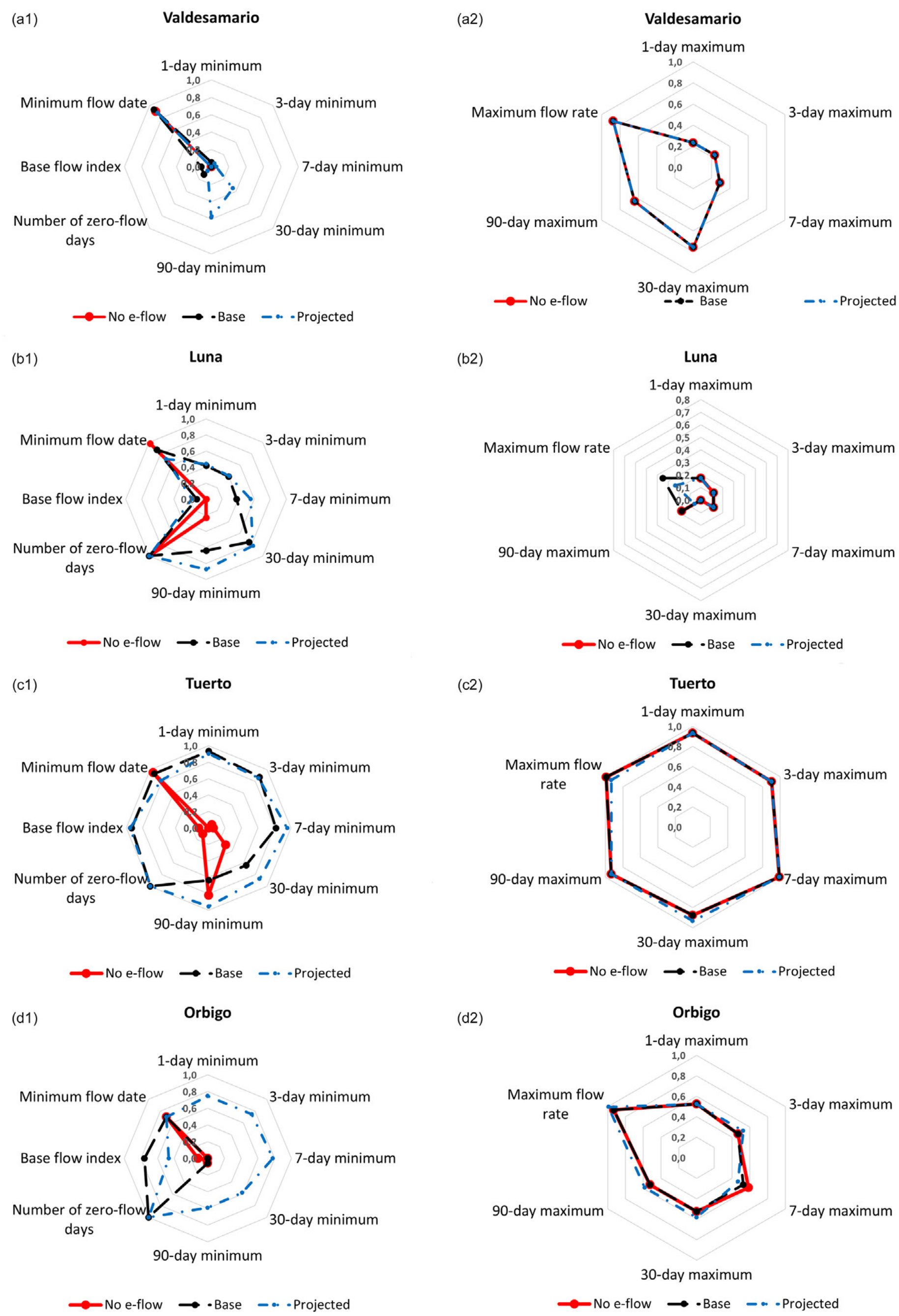

Fig. 7. Hydrological alteration indicators related to the magnitude and duration of annual extreme water conditions. (a) Valdesamario, (b) Luna, (c) Tuerto, (d) Orbigo. (1) Minimum extremes, (2) maximum extremes.

0.85); whereas the most altered stretches (lowest values of the GI) are Valdesamario and Luna. These results are in agreement with those obtained by Piqué et al. (2016) and Mezger et al. (2021), which found a significant hydrologic alteration in Spanish rivers just downstream from dams. The latter suggested the interest of assessing hydrological alteration combining variations in magnitude with changes in the timing of flows, as we have done in the present paper.

Fig. 10 also shows that the higher the values of environmental flows, the better (lower alteration) the global indicators obtained. This improvement is more evident in the stretches of the middle basin and much lower in Valdesamario and Luna, which are located in the upper part of the basin. This is in agreement with the trends and values shown in Fig. 9.

4.3. Implications on the demand reliabilities

The results of the previous section show that as the environmental flows increase, the hydrological alteration indicators also increase (improve). Therefore, the projected scenario presents better results of GIs in all the selected sections and the scenario without environmental flows presents the most unfavourable results.

However, although one of the main objectives of hydrological planning is to protect water bodies and ecosystems, it should also try to guarantee all the demands of water, regulating its use to preserve the environment. For this reason, in addition to the effects of the environmental flow regimes in the hydrological alteration previously analysed, the implications on the reliabilities of the demands in the basin must also be quantified. Since the reliabilities of urban demands are fulfilled

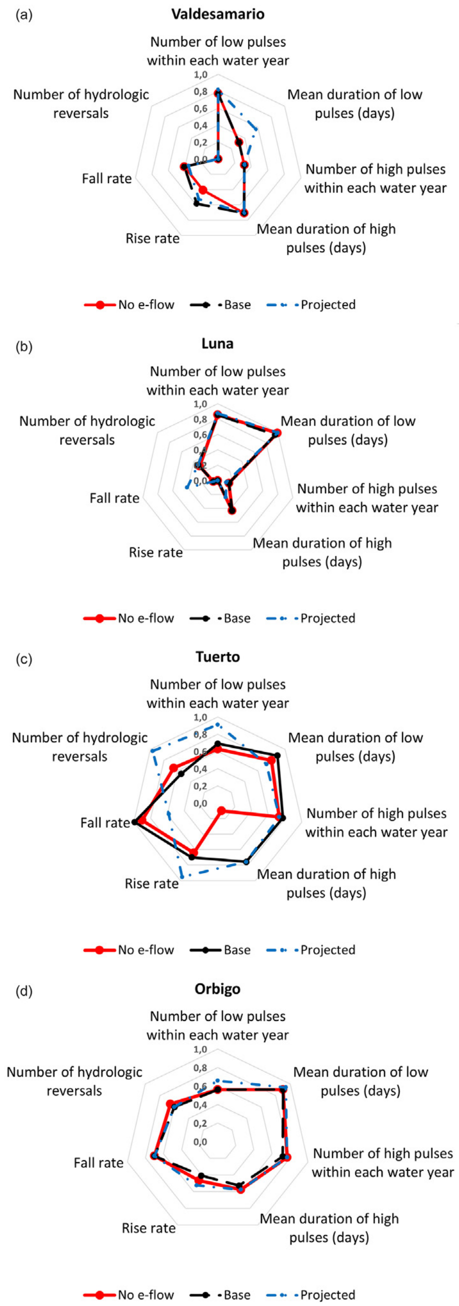

Fig. 8. Hydrological alteration indicators related to the rate, frequency and duration of pulses and changes in hydrological conditions. (a) Valdesamario, (b) Luna, (c) Tuerto, (d) Orbigo.

in the three scenarios, in this section the annual, biannual, and decadal reliabilities of agricultural demands are evaluated according to the criteria established in the Spanish water planning regulations (MARM, 2008).

Fig. 11 shows the results obtained for the three scenarios initially considered (base, no e-flow and projected). The values that fulfil the reliabilities criteria are shown in green and those that represent reliability failures are marked in red. The general trend of the demands reliabilities is in accordance with the restrictions imposed in the scenarios. Thus, in the scenario with the highest environmental flow values (projected scenario), most of the demands experience failures for the three reliability criteria.

Consequently, during the decision-making process related to the elaboration of the Hydrological Plan 2022–2027, it was decided to modify (reduce) the projected environmental flows. The results of the

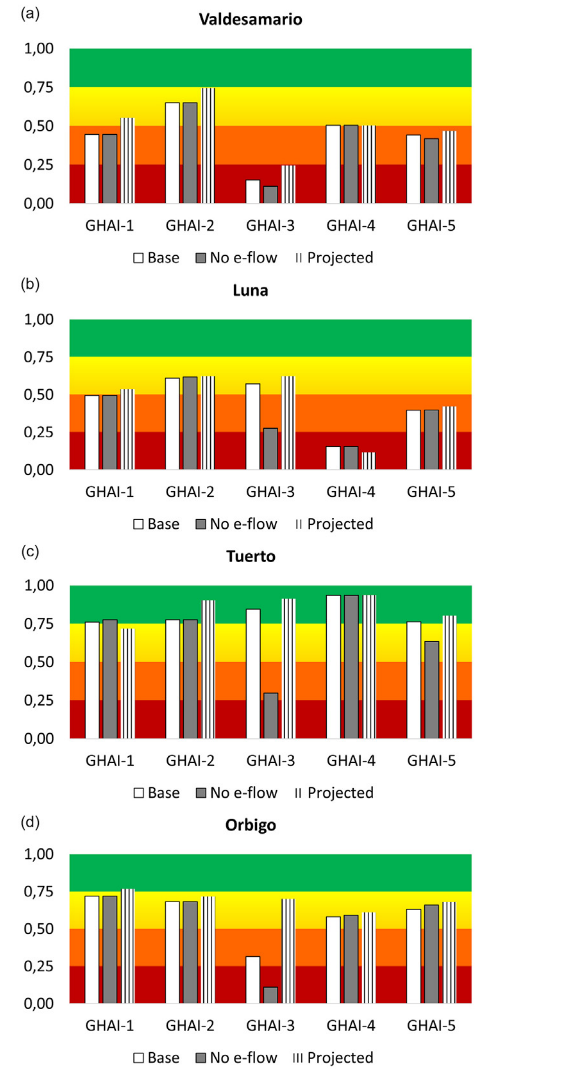

Fig. 9. Values of the grouped hydrological alteration indicator (GHAI) in the analysed river stretches for the three scenarios. (a) Valdesamario, (b) Luna, (c) Tuerto, (d) Orbigo.

reliabilities for the finally projected environmental flow regimes (projected 2 scenario) are also shown in Fig. 11. It is observed that in the projected 2 scenario the reliabilities failures are significantly reduced with respect to the projected 1 scenario. Thus, the projected 2 scenario considerably improves hydrological alteration with respect to the base (current) scenario, without significantly affect the demand reliabilities.

Fig. 11 shows that there are four agricultural demands that do not fulfil the reliabilities criteria in any of the scenarios considered. These

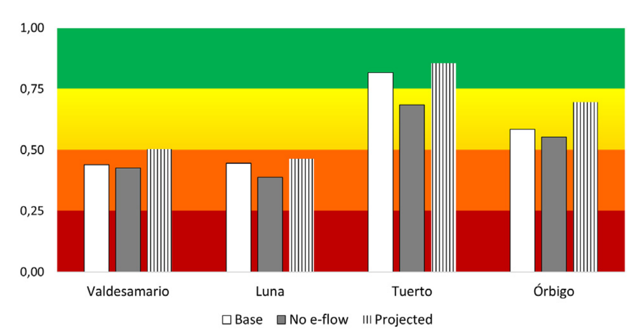

Fig. 10. Values of the global hydrological alteration indicator in the analysed river stretches for the three scenarios.

	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	No e-flow	28	9	9	18	5	11	19	13	53	0	30	5	35	14	69	10	30	69	2	11	29	58	5	4	0	9
	Base	31	10	10	17	11	16	27	9	53	0	31	26	35	28	69	12	32	69	30	17	29	72	30	0	0	16
	Projected 2	34	32	30	39	48	44	30	0	53	0	50	26	75	30	69	43	47	69	41	40	49	67	43	0	0	44
	Projected 1	95	81	76	92	83	81	84	0	53	0	95	83	100	90	69	77	86	69	92	76	90	100	97	0	0	78
Biannual	No e-flow	28	9	9	18	5	11	19	13	92	0	30	5	35	14	128	10	30	116	2	11	43	58	5	4	0	9
	Base	31	10	10	18	11	16	33	9	92	0	31	26	35	36	128	12	32	116	30	17	43	94	30	0	0	16
	Projected 2	42	41	41	42	52	48	55	0	92	0	57	26	109	51	128	46	57	116	42	43	59	98	43	0	0	48
	Projected 1	164	141	135	159	144	140	131	0	92	0	164	122	174	142	128	131	149	116	150	130	156	196	159	0	0	135
Decadal	No e-flow	36	11	12	43	8	13	19	13	283	0	37	5	36	14	543	12	37	355	2	12	69	120	5	4	0	11
	Base	39	16	15	42	19	24	57	9	283	0	37	43	36	59	543	20	39	355	54	24	69	161	54	0	0	23
	Projected 2	94	87	80	81	94	114	95	0	283	0	115	47	214	88	543	103	125	355	69	100	144	199	78	0	0	105
	Projected 1	462	353	340	471	430	429	258	0	283	0	494	207	553	275	543	406	455	355	274	397	467	419	277	0	0	415

Fig. 11. Annual, biannual, and decadal reliabilities obtained for the three scenarios initially considered (base, no e-flow and projected) and for the scenario finally projected. The numbers of the first row are referred to the agricultural demands shown in Fig. 12.

demands are indicated in red in the topology of the model shown in Fig. 12. It is observed that the four demands that present failures are found in the westernmost part of the basin.

5. Conclusions

In this work, a methodology to quantify the implications of environmental flow regimes on the hydrological alteration of river stretches is presented. The methodology is mainly based on the implementation and calibration of a water allocation model, the estimation of the natural flow regime; and the computation, normalization, and aggregation of indicators of hydrological alteration.

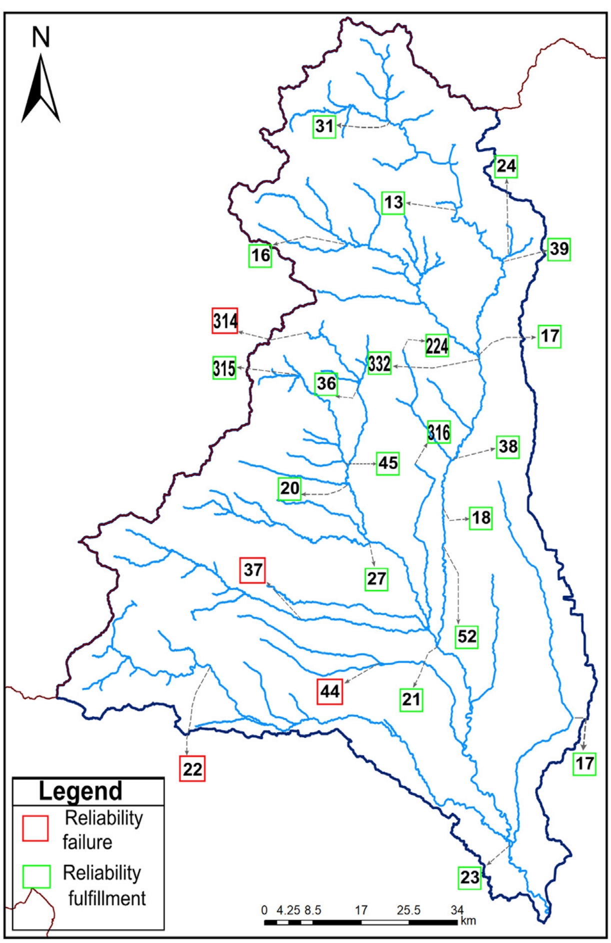

Fig. 12. Topology of the model generated in SIMGES. The river agricultural demand units with (without) failures in the demand reliabilities are marked in red (green).

The methodology was illustrated through a case study in the Orbigo River basin (Iberian Peninsula). Three management strategies of environmental flows were modelled with the SIMGES model: the current environmental flow regime (base scenario), a regulated scenario assuming that there are no environmental flows, and a regulated scenario that represents the environmental flows initially projected in the Hydrological Plan of the basin for the period 2022–2027. Based on the results of SIMGES, the indicators of hydrological alteration were analysed in four river stretches with different locations and characteristics: Valdesamario, Luna, Tuerto, and Orbigo.

The greatest values of the global indicator of hydrological alteration (i.e., the least altered conditions) were obtained in the Tuerto river. All the results confirmed that the higher the values of environmental flows, the greater (lower alteration) the global indicator values obtained. This improvement was lower in Valdesamario and Luna, which are located in the upper part of the basin.

The effects of the environmental flow scenarios on the demand reliabilities were also quantified. It was obtained that in the initially projected scenario most of the demands experience failures for the three reliability criteria. The demand reliabilities obtained were in accordance with the restrictions imposed in the environmental flow regimes: the greater the environmental flows, the greater the failures obtained in the demand reliabilities.

The results presented in this paper reveal that the proposed methodology is a useful tool to support the design of management strategies of environmental flow regimes that allow the optimum combination between fulfilment of the water demands and improvement of the hydrological status of rivers. The main contribution of this work to the current knowledge is the definition of a global indicator of the hydrological alteration of river stretches, which is obtained through simulations with a water allocation model on a daily scale. The definition and assessment of indicators of potential habitat alteration in regulated river basins represent research challenges to be addressed in the future to complement the hydrological alteration indicators analysed in this paper.

CRediT authorship contribution statement

Valentina Monico: Methodology, Software, Investigation, Writing – original draft. **Abel Solera:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Rafael J. Bergillos:** Methodology, Formal analysis, Investigation, Writing – original draft, Supervision. **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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