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Research paper

Challenges to barbel population resilience due to hydrological alteration

CAROLINA GALLO, *Laboratory of Zoology, Department of Forest Engineering, Technical University of Madrid, Ciudad Universitaria, SN Madrid 28040, Spain. Email:* c.gallogranizo@gmail.com

CARLOS ALONSO, *Laboratory of Zoology, Department of Forest Engineering, Technical University of Madrid, Ciudad Universitaria, SN Madrid 28040, Spain. Email:* carlos.alonso@upm.es

DIEGO GARCÍA DE JALÓN, *Laboratory of Zoology, Department of Forest Engineering, Technical University of Madrid, Ciudad Universitaria, SN Madrid 28040, Spain. Email:* diego.gjalon@upm.es *(author for correspondence)*

ABSTRACT

This study aims to evaluate how the habitat of the Iberian barbel (*Luciobarbus bocagei*) has changed over the last nine decades in a reach of the River Duero in Toro (Zamora). The available physical habitat through different streamflows was quantified as the wetted area potentially usable by adult barbel with maximum preference (weighted usable area [WUA]). Historical time series of streamflows were used to generate a time series of habitat. Flow data were studied from 1912 to 2008, period being divided into three sub-periods. The sub-period 1912–1931 was considered as a natural regime of reference, and sub-periods 1942–1980 and 1981–2008 were altered. Data from 1931 to 1942 were missing. Uniform continuous under-threshold (UCUT) curves were developed for a set of WUA thresholds from 20% to 75% maximum WUA in the three different sub-periods. As Iberian barbel's life- history traits determine that habitat conditions become limiting during summer season, we have drawn UCUT curves using the values from July to September. In order to quantify the challenges to population resilience due to changes in habitat availability, an index of population fatigue was proposed (analogous to materials fatigue), which compares altered periods to natural one. This index was defined by the difference between the area that the UCUT curves in the altered and natural periods draw for each defined threshold and it is measured in days under thresholds. The index of population fatigue is calculated as an extension of Parasiewicz *et al.*'s (2012) concept of habitat stress days alteration, the HSDA, into an integrated HSDA (IHSDA). The greater the index value, the greater the alteration suffered. Results showed an increasing loss of habitat availability for common events related to natural conditions: 10 days for the first altered sub-period that became more evident (up to 18 days) in the last sub-period.

Keywords: Resilience alteration; flow regulation; continuous uniform under-threshold (UCUT) curves; index of population fatigue

1 Introduction

The economic development of the countries has been linked to a greater consumption of water resources. Worldwide rivers are increasingly degraded due to growing water demand (mainly for water supply, agriculture and industry), resulting in a loss of goods and services that they can provide and implying further disturbance of the natural flow regimes and fluvial ecology. From the need to use these resources without endangering aquatic ecosystems, the concept of environmental flow was born, initially set at a minimum value which maintains the ecological conditions needed for survival (generally 10% of the mean flow). Clearly, this minimum value should not be applied to a single flow value but to a set of values (Petts 1996, García de Jalón 2003) that preserves the main ecological conditions to help achieve natural flow regimes (Poff *et al.* 1997).

Harper *et al.* (1992) identified the physical habitat as a fundamental unit on which to base the recommendations in river conservation. The physical habitat of the river represents the space that can be used by a fish species and a certain stage of development (Milhous *et al.* 1990). Furthermore, Maddock (1999) stated that the physical habitat provides a natural link between the physical environment and its inhabitants, being a very useful element to consider when evaluating the state of the river.

Developing habitat modelling methods that capture the spatial distribution of habitat is necessary for the understanding of ecological processes. There are different methods of habitat modelling normally in one or two dimensions, although there are models developed in three dimensions (Booker *et al.* 2004). The first system developed to systematically simulate the physical habitat and generate habitat time series was PHABSIM (Physical Habitat Simulation, Milhous *et al.* 1981). Since its

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creation, PHABSIM has been widely used in different parts of the world (Parasiewicz and Dunbar 2001, Booker and Acreman 2007), but it has the limitation that it does not model many interactions between species, life stages and other variables influencing the state of ecosystems (Milhous 1999). In Spain, in addition to PHABSIM, other simulation systems have been used to obtain habitat requirements in terms of weighted usable area (WUA) (m^2), for instance, RHYHABSIM (Jowett 1989), River2D (Steffler 2000) or MesoHABSIM (Parasiewicz 2007, Parasiewicz *et al.* 2009).

Using the WUA vs. flow function and flow time series, physical habitat time series can be generated. This series of physical habitat can be used to evaluate an action or a project of water management such as a determination of environmental flows project (Milhous 1986, 2004). The concept of using time series analysis of the habitat variation comes from the Washington Department of Ecology (Clarke 1976) and the Geological Survey of the United States (Collings *et al.* 1972). By studying the habitat, time series was essential to consider not only the magnitudes of impacts in evaluating the potential habitat conditions for fish communities but also their duration and frequency (Poff *et al.* 1997, Richter *et al.* 1997). For this purpose, uniform continuous under-threshold (UCUT) curves were developed. These curves represent the duration under a given WUA threshold vs. cumulative continuous durations in percentage of the studied period. Therefore, their use can help assess the environmental thresholds to which the species are subjected (Capra *et al.* 1995, Parasiewicz 2008). In Spain, there have been several studies carried out to assess the availability of habitat and environmental flow regimes using the continuous under-threshold curves (Sanchez *et al.* 2007, Paredes-Arquiola *et al*. 2011).

From the need to include ecological components in river management, holistic methods were born (King *et al.* 2003, Tharme 2003). Within the ELOHA framework (*Ecological Limits Of Hydrological Alterations*), Poff *et al.* (2009) argue that relationships between flow alteration and ecological characteristics for different types of rivers are a key element that must unite the hydrological, ecological and social aspects of environmental flow assessment.

Holling (1973) defined ecological resilience as the property of an ecological system that determines the persistence of relationships within the system. A fish population stands by its ability to overcome abrupt, unexpected, however natural, changes in habitat availability. When a highly intense event decreases habitat below a given threshold, it may take longer for the population to recover. And this may also be expectable when events of moderate intensity are repeated in a short period or if the decreased habitat conditions last longer. It is, therefore, expectable that the intensity of the habitat disturbances as well as their frequency and duration may challenge the ability of the population to overcome these disturbances. Due to its analogy with the concept of loads challenging mechanical structures in engineering, this challenge to population resilience may be treated as 'ecological loads'.

The main objective of this work is to quantify these ecological loads by knowing how much the availability of habitat for a fish species has changed over time in relation to variations in flow in the studied river section.

With this aim, Parasiewicz *et al*. (2012) defined the concept of habitat stress days alteration (HSDA), which can be used for comparative analysis of actual vs. reference conditions. HSDA compares two different UCUTs obtained for the same threshold but different conditions (reference vs. actual), and it does it for several particular continuous durations below threshold.

However, a more accurate estimation of the habitat loss can be obtained by considering not only several but all the possible continuous durations below threshold. For this purpose, here we present a method to quantify the loss of habitat through time by quantifying the area contained between the UCUT in reference hydrological conditions and the UCUT in actual conditions, both calculated for a given threshold. The metric thus defined is an extension of the HSDA into an Integrated HSDA (IHSDA). We applied these new metric to quantify the habitat loss of an Iberian barbel (*Luciobarbus bocagei*) population by analysing the habitat time series with continuous duration curves.

2 Study area

This research was carried out in a section of the River Duero. The river section object of this study is in the municipality of Toro, province of Zamora (Figure 1). It comprises a length of 16 km from the River Hornija to the Regato de Valdelapega. The average width of the river along its length is about 100 m. Historical flow data were obtained from the Toro station of the Official Network of Gauging Stations (Number 62) of the Duero Basin Authority.

3 Methods

The historical data flow cover hydrological years from 1912 to 2008 with a break corresponding to the years of Civil War. Three sub-periods were considered. The first period was 1912–1931 and was considered natural, since within that time there was very little human intervention in the River Basin upstream the control point (until 1930 there were only two dams built upstream). Between 1932 and 1941, there were no records from the gauge, and the greatest dams were built during the 1930s (Camporredondo Dam with 69.8 hm^3 of capacity, 1930; Arlanzón Dam with 20.1 hm^3, 1933) and early 1940s (Requejada Dam with 65 hm^3, 1940; Cuerda del Pozo Dam with 229.2 hm^3, 1941). For these reasons, period from 1942 till 2008 was considered altered. This period was further divided into two sub-periods not attending to an equal duration but taking into account their similar monthly flow pattern, being finally divided into 1942–1980 and 1981–2008.

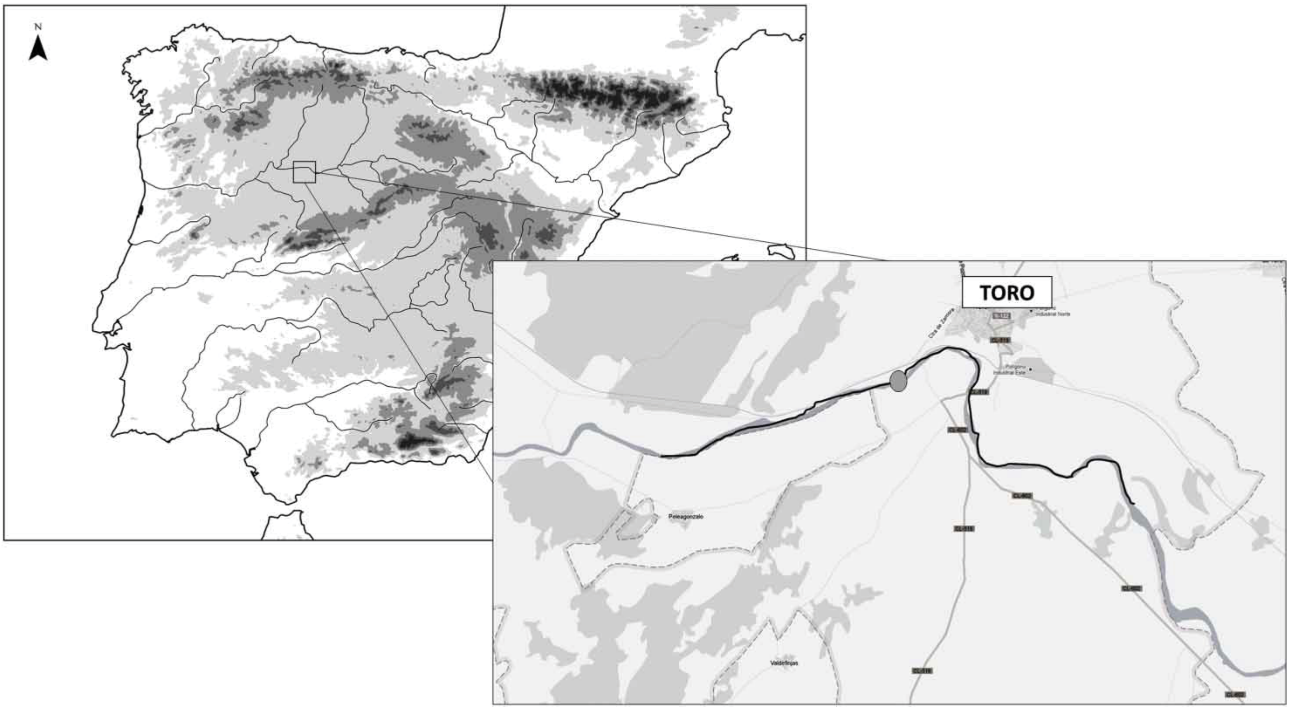

Figure 1. Location map of the study area and control point.

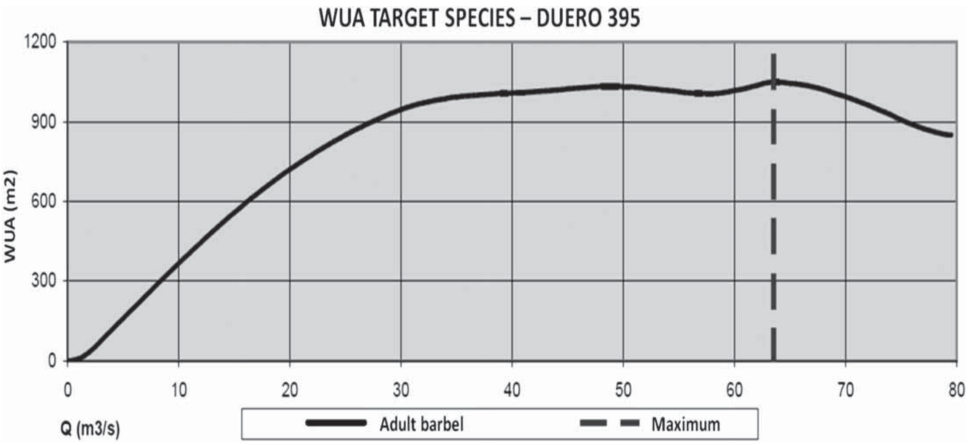

Figure 2. Relationship between streamflow and WUA for the adult barbel in the River Duero.

The WUA-flow relationship curve (Figure 2) that was developed by the Duero River Basin Management Plan (CHD 2010) was used for the target species (barbel: *L. bocagei*) in adult stage, and using the flow time series, habitat time series were generated for the three different sub-periods. The maximum WUA value (1062 m^2) is reached when the flow is 63.5 m^3/s (Figure 2). The WUA–flow graph for the adult barbel comprises only flow values from 0 to 80 m^3/s. Among the data recorded, there were flows greater than 80 m^3/s. Therefore, it had to be assumed that from this value, the curve tends to stabilize and a WUA of 855 m^2 was set as balance value.

For the analysis of habitat time series, the UCUT curves proposed by Parasiewicz (2008) were used. These curves represent, in ordinates, the duration under a given WUA threshold and cumulative continuous durations in percentage of the studied period in abscissa. As Iberian barbel life-history traits determine that habitat conditions become limiting during dry season (summer in Mediterranean countries), we have drawn UCUT curves only for the dry season (using the values from July to September), when there are greater problems in terms of habitat due to reduced flow.

A total of 12 UCUT curves were developed for different thresholds of habitat (from 20% to 75% of the maximum habitat, with intervals of 5%). This procedure was followed for the three sub-year periods separately. For each defined threshold, in the WUA–time curves, continuous periods during which the habitat availability in the river section was below that value were counted, arranging them from the

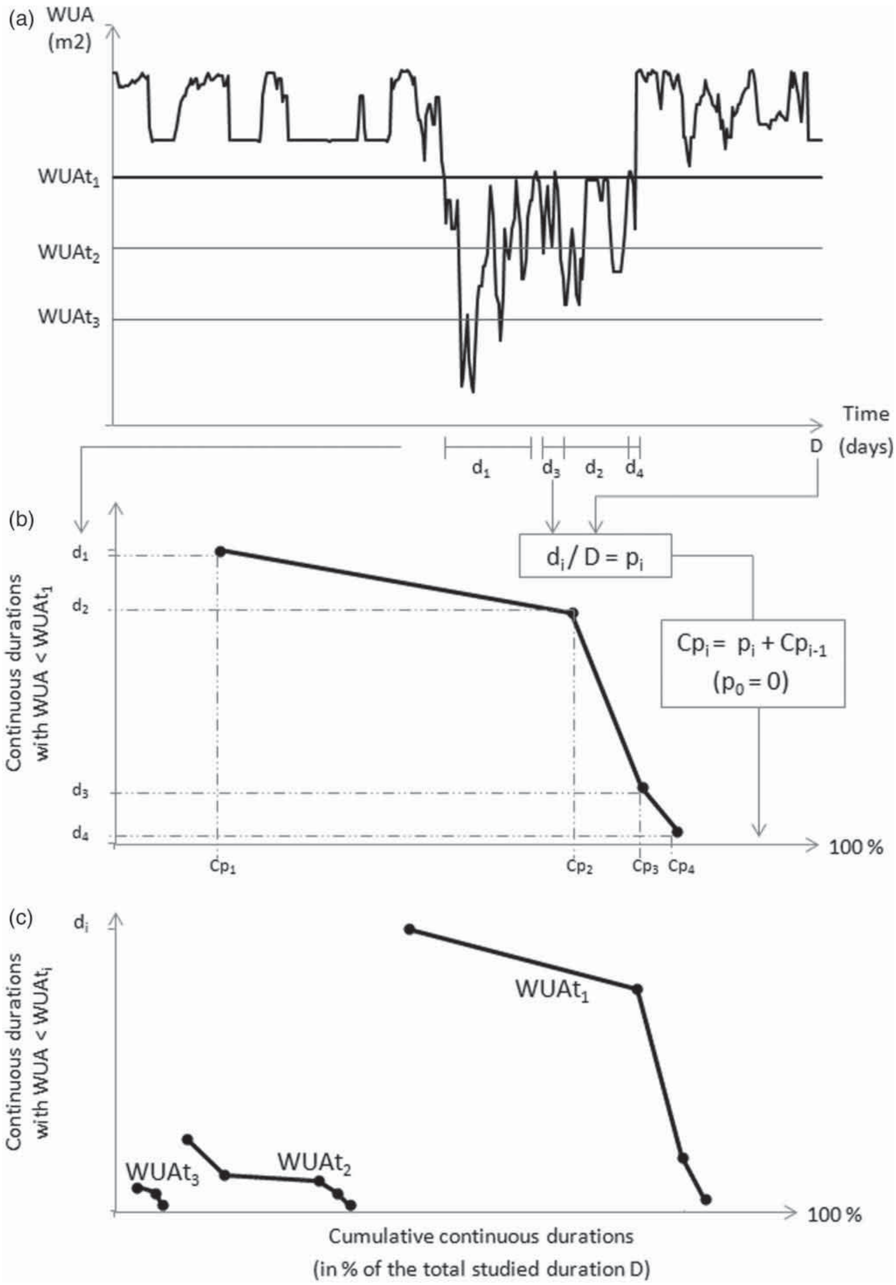

Figure 3. Construction of continuous under-threshold curves from the habitat time series curves.

longest to the shortest one. Thus, a cumulative frequency curve was obtained in percentage of the total studied duration (Figure 3). Following the Parasiewicz's methodology, the continuous durations with 0% of cumulative increase were also included in this study.

Once plotting all the curves in the same graph, the accumulation of curves allows defining environmental thresholds and types of events. Thresholds for rare, critical and common events were defined by the observation of a sudden increase in frequency in the graph (Parasiewicz 2008).

Considering the differences between the habitat availability in natural and altered sub-periods, an index was calculated by the difference between the area limited by the UCUT curve of a certain threshold and both axis in altered periods and the corresponding area in the natural period (without alteration) (Figure 4). This newly developed index can be considered an estimation of the HSDA in an integrated way, and therefore, we call it 'Integrated Habitat Stress Days Alteration'.

The graph area between the curve and the horizontal axis is obtained by adding the areas of the trapeziums bounded by four points on the graph. The total area is calculated as follows:

$$A = \sum \left\{ \frac{(y_i + y_{i+1})}{2} \cdot (x_{i+1} - x_i) \right\}, \tag{1}$$

where (x_i, y_i) and (x_{i+1}, y_{i+1}) are the coordinates of the two points on the curve defining the trapezium.

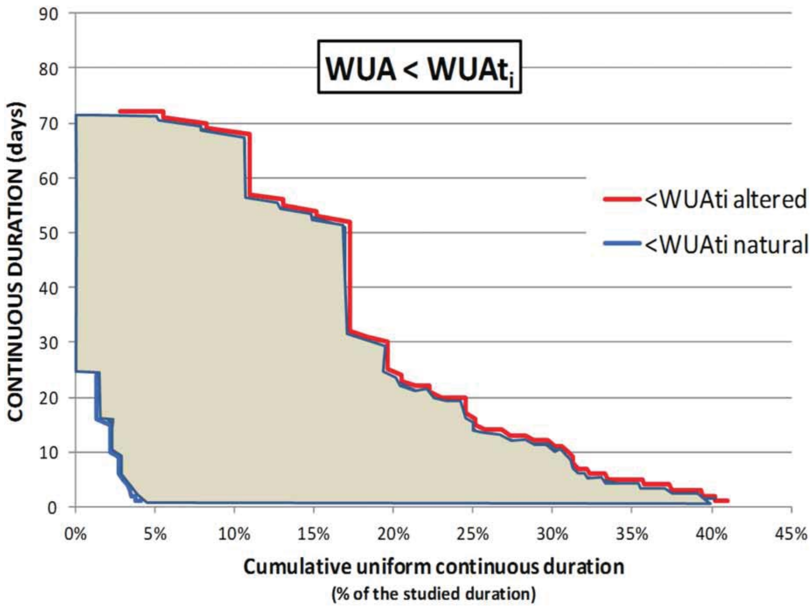

Figure 4. Calculation of the 'IHSDA'. The area between curves represents the value of the index.

4 Results

Considering the habitat time series, the results showed a normal fluctuation in habitat between 800 and 1100 m^2, with annual critical conditions in which the habitat appreciably fell (Figure 5(a)). These critical conditions occurred during the dry season, period that coincides with the maximum biological activity of the species. It was found that during the 19 years of the first period defined as natural, habitat was found below 600 m^2 on seven occasions and only one of them fell below 200 m^2.

During the two altered periods, the habitat was usually less than 600 m^2; even numerous times fell below 400 and 200 m^2. This situation was accentuated in the last period. The frequency at which the WUA decreased below 200 m^2 increased 5.3 times in 1942–1980 (Figure 5(b)) and 9 times in 1981–2008 (Figure 5(c)) compared with the 1912–1931 period.

From the temporal distribution of habitat of the natural period, a set of UCUT curves was obtained (Figure 6(a)).

Curves in the lower left represent rare events (low cumulative duration). The horizontal distance between the curves indicates the change in frequency of events associated with an increase in habitat to the next level (e.g. the greater the distance between the two curves in the same continuous length, the greater the change in frequency of events). Therefore, moments when habitat availability was *rare*, *critical* or *common* were set for the natural sub-period looking for specific regions in the graph with a greater or lesser concentration of curves. The *rare* habitat events occur infrequently and only for a short time, and in the framework of management, they should be exceeded most of the time. *Critical* levels define more frequent events during which the circumstances of habitat decrease rapidly to *rare* level. And the common habitat levels are the highest defined and should define the beginning of the normal circumstances of less common events, and at this level, there is no stress.

Observing the graph of UCUT curves in the natural period, thresholds that produce stress were selected: *rare* when the habitat availability is 30% of the maximum WUA, *critical* at 55% and *common* at 70%.

UCUT curves drawn for the altered periods had a much less defined pattern in comparison with the natural period (Figure 6(b) and 6(c)). The space between curves in these periods was uniform, with no distinguishing areas of concentration of curves.

The IHSDA showed a maximum loss of habitat occurred in the common events. During the first altered period (1942–1980) related to natural conditions, the habitat reached 10 days % of habitat loss and 8 days more during the last period (Figure 7). In the critical events (55% WUA max), the loss was 9.8 days during the first period and 13.9 days during the second one. In the threshold of rare events (30% WUA max), the loss was 4 and 5 days, respectively, for the two altered periods.

5 Discussion

A general decrease in flows was observed. It means less availability of flow and, therefore, of habitat which causes stress on fish species. The results are consistent with the hypothesis that alteration of flow regimes affects aquatic organisms in relation to the degree of disturbance (Poff *et al.* 1997, Bunn and Arthington 2002, Freeman and Marcinek 2006).

Water pollution, overexploitation, invasion of alien species, destruction of habitat and modification of flow regime are the ultimate factors that threaten the biodiversity of freshwater ecosystems (Elvira 1995, Malmqvist and Rundle 2002, Dudgeon *et al.* 2006). In the present case, one of the causes producing stress on *L. bocagei* was the variation in streamflows. Similar results were found by Sánchez *et al.* (2007) analysing the

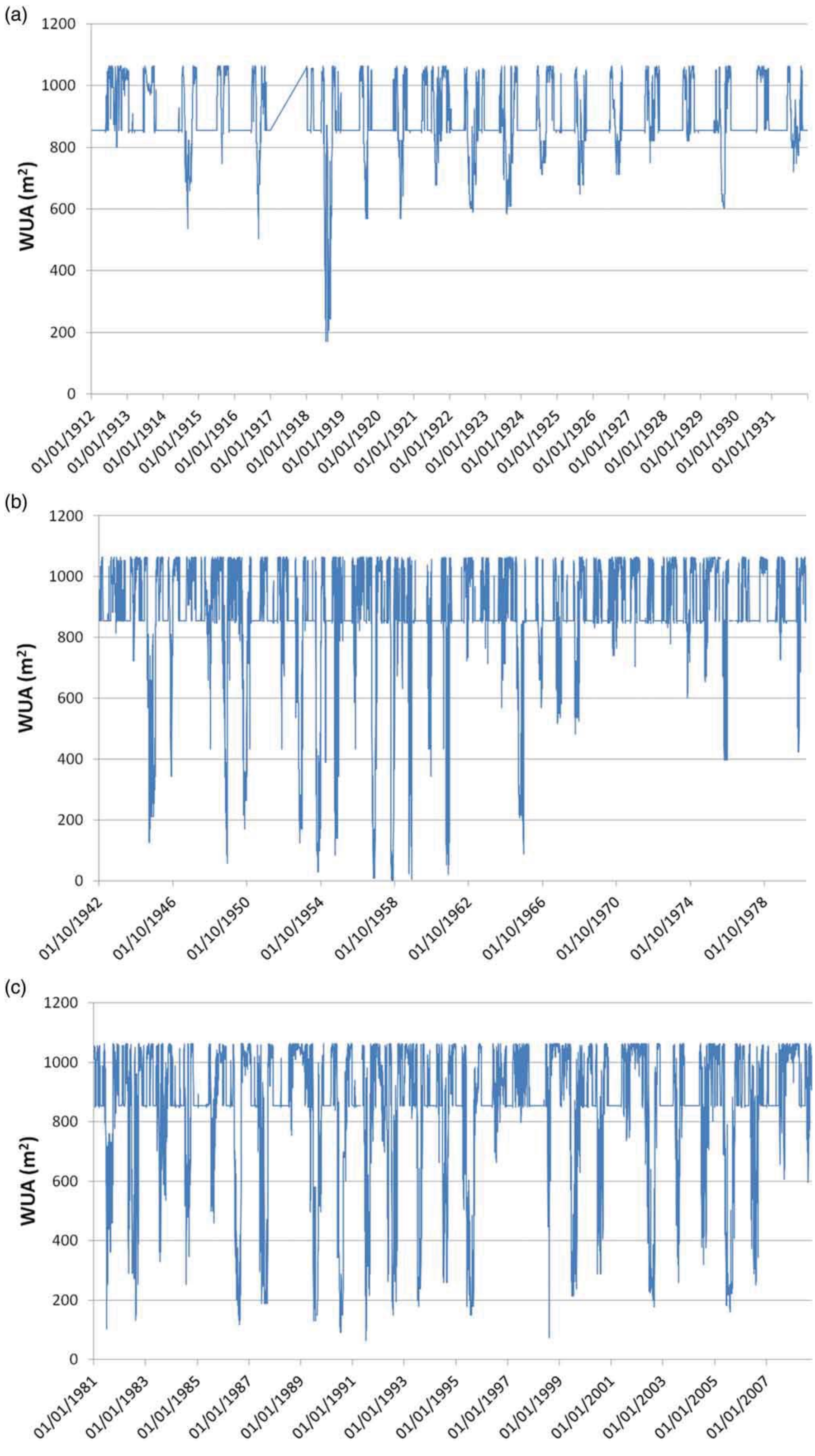

Figure 5. Habitat time series for the three different sub-periods: (a) 1912–1931; (b) 1942–1980 and (c) 1981–2008.

habitat of *Chondostroma arrigonis* in the Rivers Júcar and Cabriel, using the Capra *et al.* (1995) methodology.

In natural conditions, the UCUT curves present different areas with higher concentrations of curves and have a defined pattern. The loss of that pattern in the UCUT curves drawn for the two altered regimens and the uniformity of space between curves revealed changes in habitat for these two periods. Moreover, the total area occupied by curves was much larger than in the period 1912–1931, indicating an increase in frequency and duration of events in which the habitat for barbel is below the limits. The

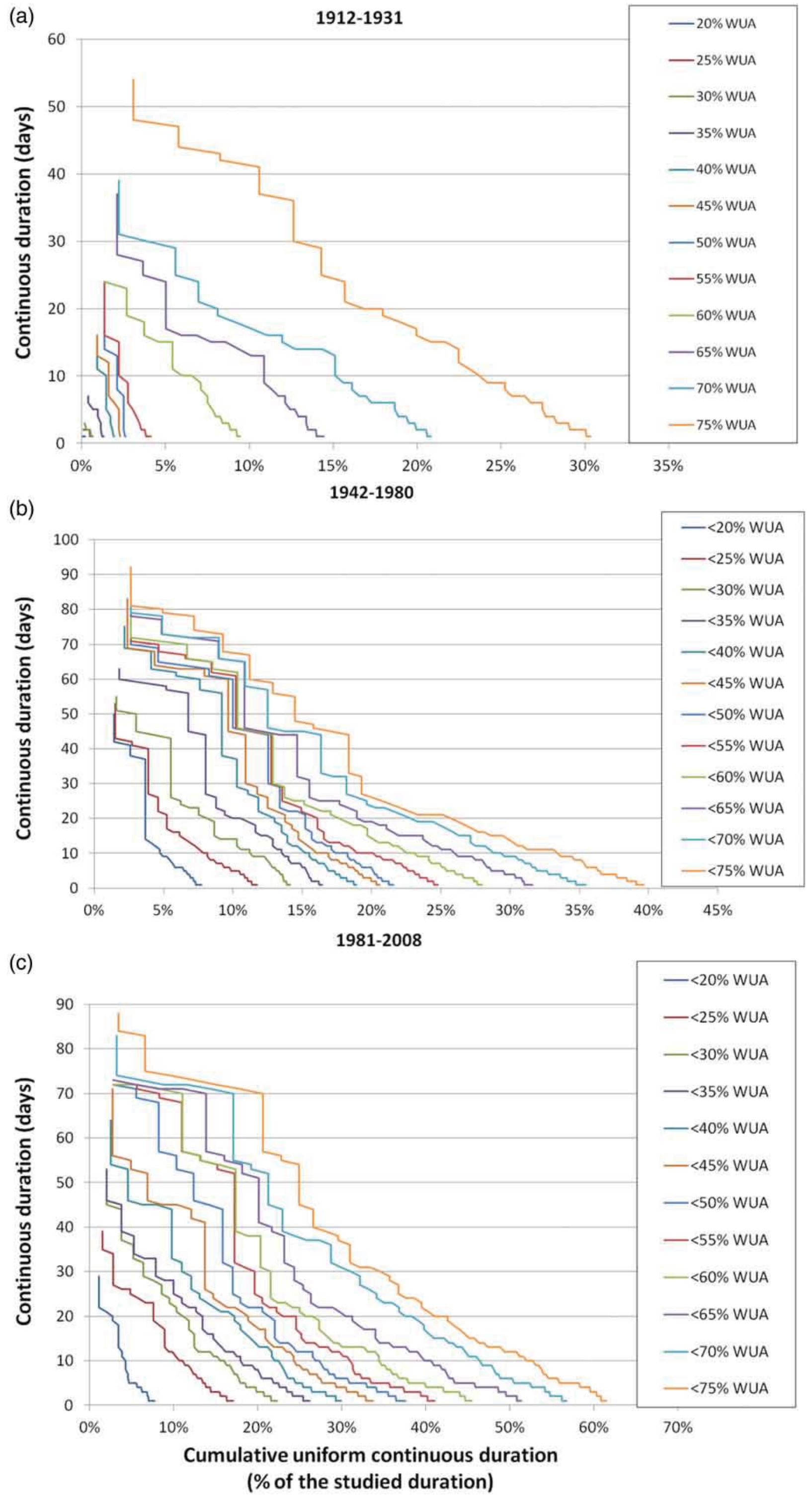

Figure 6. UCUT curves: (a) 1912–1931 period; (b) 1942–1980 and (c) 1981–2008.

rare and critical levels of habitat occur with increasing frequency. These events are not only more frequent but also much long-lasting than throughout the years in the natural regime, showing a considerable loss of habitat available to the barbel.

Habitat thresholds causing stress on barbel populations defined in this article as rare (30%), critical (55%) and common (70%) are within the range proposed by Spanish legislation (WPI 2008). When determining environmental flows, it fixes that for normal years, habitat should be in a range between 50% and 80% of the maximum habitat and for dry years, above 30%. However, Paredes-Arquiola *et al.* (2011) in an analysis of the Duero RBPM identified thatminimum threshold is 40% of maximum habitat for the whole Duero basin, higher than that defined here and in the Water Planning Instruction (WPI 2008).

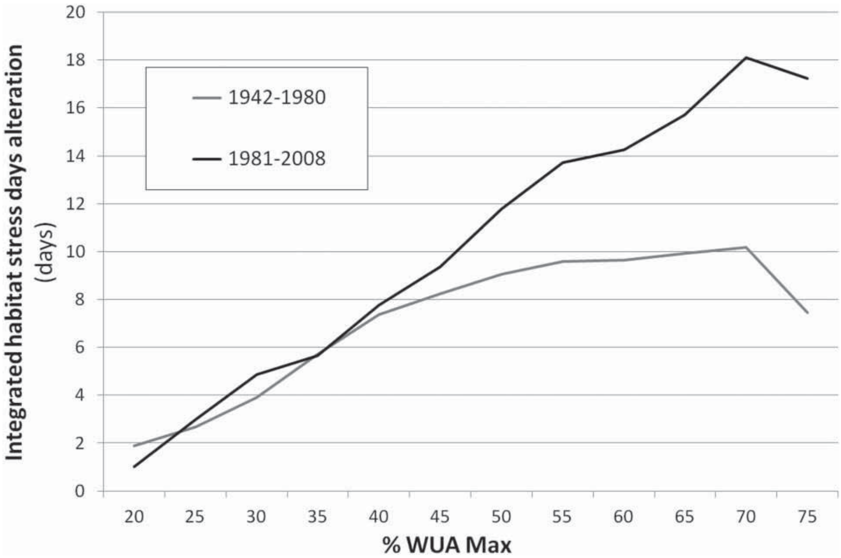

Figure 7. IHSDA. Comparing the periods 1942–1980 and 1981–2008 to the first study period 1912–1931.

In Figure 7, it is shown that IHSDA between 20% and 40% of maximum WUA take similar values in both altered periods. From 45% to 75% of maximum WUA, IHSDA was significantly higher for the period 1981–2008 than 1942–1980, indicative of a loss of resilience for adult barbel. Survival of individuals of a cohort seems to be related to usable habitat availability rather than food or other factors (Lobón-Cerviá 2003); consequently, it can be expected that current barbel population age structure is biased toward younger classes, compared with the least impacted period.

In an increasingly overexploited hydrographic network, the standards established in absolute terms, as environmental flows or minimum usable habitat, are no longer sufficient for the conservation of stocks and the structural and functional maintenance of the ecosystem, since the resilience of population deteriorates. Furthermore, in the case of highly mobile fish, river fragmentation in ever smaller segments determines their ability to recover from disturbances that droughts may cause.

The manifested decline of habitat threatens the resilience of the species to such events. This was especially important when considering the occurrence of rare events (30% of the maximum WUA), since the habitat should always be above it. The IHSDA proposed in this article detects that although the species previously had the ability to recover from events during which habitat falls below the critical and rare events, currently it is increasingly believable that it cannot withstand disturbances equally and danger of population extinction is most likely.

The present approach can be integrated in holistic methods and within the ELOHA framework, since it incorporates an ecological component which directly relates the modifications in flows to a consequence on the habitat of a certain species.

In the existing flow conditions, *L. bocagei* has suffered a significant loss of habitat. On the basis of these results, we observed how the Iberian barbel has lost part of its habitat reflected in an IHSDA of 10 and 18 days for each altered sub-period. It will be needed to calculate the IHSDA in other sites in order to know how much or little the loss is. The methodology proposed makes possible an accurate prediction of changes in habitat availability in response to human-induced changes in flow regimes of rivers.

It could be expected that repeated events will alter the population resilience. In engineering, especially in materials science, material fatigue refers to a phenomenon whereby the breakage of materials under cyclic dynamic loads occurs more easily than under static ones. In a similar manner, we may expect a population fatigue under frequent and long-lasting stress conditions. In this context, the IHSDA presented here also allows to assess and predict how a seasonal change or a hydrologic alteration will produce population fatigue. This index may be used to quantify the loss of habitat that a population can overcome before losing its potential of recovery.

This concept can be considered a way to set the threshold that once surpassed will lead the system to a different stability basin. By means of iterative calculation (iteration) in different stages of degradation until the population becomes extinct. It will then be a way to quantify the resilience of the population in terms of the amount of disturbance that it can overcome.

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