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Abstract

The physical characteristics of river habitats constitute the setting in which fluvial biota dwell and thrive. Determining the spatial and temporal patterns of physical habitat characteristics and the main factors that control them is extremely important to increase the efficiency of river management, conservation and restoration. This study determined spatial patterns of physical habitat characteristics for Atlantic and Mediterranean rivers in northern Spain and developed a river classification based on hydromorphological characteristics. Data gathered from almost 600 sites following a modified version of the River Habitat Survey methodology (RHS) were used. In addition to the usual RHS variables, the sequence of hydromorphologic units (i.e. areas exhibiting similar hydraulic characteristics, in terms of water velocity and depth), water depths and widths were recorded. Unmodified reaches were selected computing the Habitat

Modification Score (HMS). Multiple Linear Regression (MLR) models were employed to test relationships between PCAs that summarised physical river habitat characteristics with ecological relevance and environmental variables (i.e., climate, topography, land cover and geology) at different spatial scales, and used to predict physical habitat attributes for all river reaches. The density of hydromorphologic units, flow turbulence, substrate size and channel dimensions were able to discriminate river classes within the river network, with topography being the main environmental driver of habitat characteristics (although climate, geology and land cover were also relevant). This classification scheme could constitute a useful tool to restore physical habitat conditions in modified river reaches.

Key Words

River landscape, Multiple Linear Regression, Hydromorphologic Units, Classification

1. Introduction

The spatial distribution of physical characteristics along river networks influences the structure and composition of biological communities (Parsons et al., 2003; Walters et al., 2003; Álvarez-Cabria et al., 2017), ecosystem metabolism (Ogdahl et al., 2010), nutrients (Baker et al., 2012; Álvarez-Cabria et al., 2016) and potential sensitivity to anthropogenic disturbances (Baxter et al., 1999). Therefore, knowing physical habitat characteristics from hydromorphological conditions is important for water managers and river ecologists.

Physical habitat assessment is a common approach in fluvial ecology studies to characterise the physical environment and to explain the processes involved in creating spatial heterogeneity and particular physical features (Smith, 1990). A wide array of methodologies have been proposed for characterising river habitats at a range of spatial scales in order to meet different objectives (Mc Ginnity et al., 2005). These objectives (e.g., conservation, restoration, water resource management, the assessment of ecosystem integrity and geomorphic conditions) determine the habitat attributes and diagnostics to be used (Raven et al., 2010, Fernández et al., 2011). The River Habitat Survey (RHS) is the standard riverine survey method in the UK (RHS; Environment Agency, 2003; Raven et al 1997). It has been used in several countries across Europe and beyond for quality appraisal (e.g., Barquin et al 2011), habitat feature inventories (Manel et al 2000; Raven et al 2010; Walker et al 2002) and ecological research applications (e.g., habitat suitability; Hastie et al 2003; Vaughan et al 2007). Designed to characterise and assess the physical structure of fluvial ecosystems, the survey is carried out along a standard 500 m length of river channel. Flow types, substrates, channel and bank features and vegetation, as well as special features (e.g., very large boulders) are considered. Therefore, a multitude of RHS variables may be used to characterise different groups of river physical features. In this context, predicting and mapping RHS characteristics with ecological relevance (Vaughan et al 2013; Naura et al 2016) may constitute a useful tool for river research and management.

River classification is the statistical process of stratifying natural variation in measured characteristics to group and delineate similar streams and river types. In general, two main approaches have been described to classify either locations according to attributes describing environmental aspects assumed to influence stream features (the deductive approach) or the emergent properties of such features (the inductive approach; see Olden et al., 2012 for more details). Similarly, two strategies determine class definition. The 'top-down' approach is based on predefined classes, whereas the 'bottom-up' approach uses classes that result from empirical data. Specifying boundaries between classes (i.e. 'top-down' approach) has been criticised (e.g., O'Keefe & Uys, 2000; Stein et al., 2009) because it assumes that all possible classes are already known, whereas a 'bottom-up' approach may be preferable because it results in classes that are an emergent property of the data and reflect the shared similarities of key attributes (Mackey et al., 2007).

Physical grouping of streams tends to be developed following deductive 'top-down' approaches. A classic example is the Rosgen stream classification. Originally developed in the 1980s (Rosgen, 1985) and subsequently modified (Rosgen, 1994, 1996), it is a hierarchical methodology that consists of four levels of increasing specificity (channel characteristics, bed material, current condition and verification of predicted stream condition). Applications using the Rosgen classification have included stream condition assessment and monitoring, the assessment of grazing impacts on streams, aquatic habitat assessment, and stream restoration or rehabilitation (Myers and Swanson, 1992; Harrelson et al., 1994; Rosgen, 1996; Clinton et al., 1999). However, this classification scheme is associated with several types of limitations related to spatial and temporal differences in geomorphic processes, as the distinction among stream types may be somewhat arbitrary from the process perspective (Juracek and Fitzpatrick, 2003). Montgomery & Buffington (1993) developed a similar classification scheme to characterise the relative response of a river to sediment inputs. Channel types are delineated based on channel morphology, sediment transport processes, and sediment flux characteristics as controlled by hydraulic discharge and sediment supply. More recently, the Geomorphic Unit survey and classification System (GUS; Belletti et al., 2017) has focused on the classification, characterisation, analysis and monitoring of the geomorphic units present in a given reach at different spatial scales. Such a classification system was proposed in response to the lack of knowledge of physical processes in previous assessment methods (Belletti et al., 2015), but it acknowledged that further improvements might be needed to cover specific local conditions (for which it is essential to undertake fieldwork to validate).

The scientific and management utility of river classification relies on the capacity to extrapolate classes to sites without data, providing a map of natural characteristics at the regional scale (e.g., Snelder et al., 2009; Reidy-Lierman et al., 2012). The classify-then-predict strategy (ClasF) has been the most common approach to fulfil this objective (e.g., Kennard et al., 2010; Reidy-Lierman et al., 2012). ClasF predicts class membership to sites without river data based on environmental conditions (e.g., climate, topography, geology or land cover). In contrast, some researchers have attempted the predict first then-classify strategy (PredF; Ferrier and Guisan, 2006; Snelder and Booker, 2013). Using this approach, river characteristics are predicted onto the entire river network based on climate and catchment characteristics. Classification of all river segments is performed as a final stage within the procedure. Peñas et al., (2014) showed that PredF performs better than ClasF to classify flow regimes, as significant differences in the ability to discriminate hydrological characters were found between both approaches for several class levels.

The integration of catchment and local characteristics such as geology, channel confinement and channel slope by properly designed classifications may provide useful tools for water resource management. Developing and implementing environmental flow standards at regional scales ultimately requires employing accurate estimates of ecologically meaningful streamflows in rivers or river segments distributed throughout a region, including those lacking streamflow gauging records (e.g., Snelder et al., 2005; Kennen et al., 2008). A hydromorphologic classification may apply this reasoning to determine how such flows get translated into the physical habitats experienced by, and available to, the riverine biota. This is the basis of a consensus view from a group of international scientists that provided a framework for assessing environmental flow needs referred as the 'ecological limits of hydrological alteration' (ELOHA; Poff et al., 2010). Similarly, the River Styles framework (Brierley 1999, Brierley and Fryirs 2000, Thomson et al. 2001, Brierley et al. 2002) provides a meaningful basis to compare type-with-type and assess the contemporary condition of the river. Analysis of downstream patterns of River Styles and their changes throughout a catchment, among other considerations, provides key insights to determine river recovery potential. This assessment offers a physical basis to predict likely future river structure and function.

The objective of this study was to obtain a river reach classification for the northern quarter of Spain using a high-resolution drainage network and habitat variables obtained from the RHS. The specific objectives were to (1) determine patterns of variation of physical habitat attributes in river reaches, (2) assess the most important factors that determine such variability at different spatial scales (catchment, sub-catchment and reach) using environmental data, and (3) implement a procedure to predict such physical habitat attributes at large spatial scales.

2. Methods

2.1 Study area

The study area comprises the northern quarter of Spain (Fig. 1; 125 000 km^2). This area has been studied by the MARCE project (IHCantabria, 2012), with the objective to develop a Spatial Decision Support System to integrate and predict the different components of fluvial ecosystems (hydromorphological, water quality and biological information; e.g., Peñas et al., 2014 assessed the influence of methodological procedures on hydrological classification performance). It comprises the Cantabrian, Ebro and Catalan Basins.

The Cantabrian Basin encompasses several catchments that drain into the Cantabrian Sea, with a total surface of 22 000 km^2. Rivers are confined by the Cantabrian Cordillera, which is located parallel to the coast. Thus the catchments are characterized by high slopes and short lengths. This region has a humid oceanic temperate climate (Rivas-Martinez et al., 2004). Deciduous forest, scrubs and grasslands occupy more than 50% of the surface area, while agriculture occupies 10%.

The Ebro Basin covers a total extension of 85 530 km^2. It is enclosed by the Cantabrian Mountains and the Pyrenees in the north, by the Catalan Coastal Chain in the east and from northwest to southeast by the Iberian massif, which creates a dense river network in the catchment boundaries and an extended flat surface in the interior. Climate changes gradually from oceanic in the Pyrenean area (northwest) and the northern part of the Iberian massif to Mediterranean in the central Ebro depression. The precipitation regime in the Mediterranean region has its maxima in autumn and spring, and its minima in winter and summer. More than 40% of the surface is occupied by agricultural land and, thus, the catchment is subjected to intensive water resource control by more than 216 large dams and other water engineering structures.

The Catalan Basin comprises several catchments occupying a total area of 16 500 km^2 that drain directly from the Pyrenees or the Catalan coastal chain to the sea. This area is dominated by Mediterranean oceanic climate on the coast and by temperate climate in the mountains. Coniferous and broadleaf forest, scrubs, and grasslands occupy more than 60% of the surface in the northern catchments, which are progressively replaced by agricultural lands in the south.

2.2 Physical Habitat Characterisation

The river physical habitat was characterised using the RHS adapted for the MARCE project (IHCantabria, 2012). RHS observations are made at ten equally spaced spot-checks along the channel while information on valley form and land cover in the river corridor provide additional context. General information is also recorded using a sweep-up checklist that assesses the extent of features over the entire river reach (500 m). The version of the MARCE project also records the channel dimensions (bankfull and water widths and depths) at each spot-check, the presence of woody and leafy debris and the sequences of hydromorphologic units for the entire 500 m river reach. Hydromorphologic units are river segments that exhibit similar hydraulic characteristics, in terms of water velocity and depth. Nine types were identified: cascade, pool, trench flow, glide, run, rapid, riffle, step and waterfall (definitions in Table 1). They are based on the hierarchical approach to classify stream habitat features (relevant from an ecological perspective) developed by Hawkins et al., (1993), built on hydromorphological properties of channel units, and on definitions of the RHS protocol (Environment Agency, 2003). These modifications, in the context of the MARCE project, provide additional information that allows comparing transects located in small tributaries with those located in large main stems (as the latter could result less effectively characterised, in comparison, using the original methodology).

We assessed the artificial modification to the physical structure of the channel calculating the Habitat Modification Score (HMS; see Raven 1998). The HMS is independent of river type and its value depends on the number and type of artificial modifications present in a river reach. Point scores are based on the relative impact of modification on habitat features. By assigning a score to the different types of modification, a cumulative HMS score was used to summarise the severity and extent of alteration to the channel by local river reach pressures.

The survey was carried out from July to September (2010), in order to characterise the low-flow season, when most physical attributes of river channels are easily recognised (i.e. sediment bars, bank profiles and channel sediment; Environment Agency 2003). This ensures that the different transects are comparable, as they are surveyed in absence of floods that may alter physical habitats. Among the 574 sites surveyed in the study area, only 168 were retained for subsequent analysis based on the absence of artificial structures in the river. Thus, 406 sites were removed because of the presence of water infrastructure upstream or HMS values greater than 200, which indicates that river physical habitat is modified (Environment Agency, 2003).

A set of 23 variables were selected from the RHS data and organised in 4 different groups: 1) sequence of hydromorphologic units, 2) flow types, 3) substrate types and 4) channel dimensions. The first three groups include semi-quantitative variables relevant for river communities, whereas quantitative variables related to channel dimension allowed distinguishing between large and small reaches (Table 1). Different pre-treatments were employed depending on the group in order to summarize the information at site scale. First, the relative proportion (Rel) and the density (Dens) of each type of hydromorphologic unit were obtained for each site by dividing their count by the total number of hydromorphologic units and by the surveyed length in each site (not all sites allowed to survey 500 m. due to the presence of obstacles such as riparian vegetation), respectively. The Rel and Dens of all hydromorphologic units were used as new variables together with two additional densities: one computed on the count of types of hydromorphologic units and another computed on the number of occurrences of hydromorphologic units combined (independently of the type). Second, flow and substrate types (Table 1) were counted only in those sites where at least eight spot checks (out of the ten that the procedure establishes) were sampled. This allowed discarding those sites where a representative length was not sampled due to the presence of obstacles. Finally, the channel dimensions were averaged among spot-checks (also, if eight or more had been recorded). These selection criteria reduced the number of sites available to analyse flow and substrate types to 68, and the number to analyse channel dimensions to 67.

2.3 Environmental information at different spatial scales

A Synthetic River Network (SRN) delineated from a 25 m Digital Elevation Model (DEM) developed by the National Geographic Institute (IGN), through the NetStream software (Benda et al., 2007), allowed the assessment of the main determinants of habitat variability at different spatial scales. The scales were: i) catchment (the entire area draining to the survey unit); ii) sub-catchment (area draining only to the survey unit); and iii) reach. The SNR has already been used to model communities (Álvarez-Cabria et al., 2017), water quality (Álvarez-Cabria et al., 2016) and flow characteristics (Peñas et al., 2014; 2018) in the study area. It comprises 667 406 segments with lengths ranging from 16 to 800 m and was used as a virtual hydrologic network to integrate environmental variables estimated from various sources of available digital cartographical information: topography, climate, land cover and geology (Table 2). Topographical variables were derived from the 25 m DEM. Climatic variables were obtained from 1 km-resolution maps created by the Centre for Studies and Experimentation on Public Works (CEDEX) interpolating series from the Spanish weather station network (Estrela et al., 1999). Land cover categories were derived from the layers (1:25 000) in the System of Information on Soil Occupation in Spain (SIOSE). Geologic variables were obtained through cartography 1:200 000 elaborated by the Geological and Mining Institute of Spain (IGME), deriving hardness semi-quantitatively from categories in maps (see Snelder et al., 2008 for details).

2.4 River classification

The procedure was based on obtaining synthetic habitat information for the whole SRN using a predict first then-classify strategy (PredF; see Introduction), in order to fit empirical models as a function of the environmental variables in the corresponding stream segment. For this purpose, we reduced the dimensionality of the semi-quantitative RHS variables by performing three sets of Principal Component Analyses (PCA). In other words, we examined dominant patterns of intercorrelation among the variables associated with hydromorphologic units, flow types and substrates and identified subsets that describe the major sources of variation while minimizing redundancy or multicollinearity. The Broken Stick Method was used to confirm that the number of Principal Components to keep was greater than one. Using these PCAs, we reduced the initial number of RHS variables to two PCA axes per semi-quantitative set of RHS variables (hydromorphologic units, flow types and substrates) plus the four quantitative variables associated with channel dimensions, after verifying the absence of cross-correlation ($|r| < 0.7$; Dormann et al., 2013).

Empirical models were initially fitted one at a time as a function of environmental variables through Multiple Linear Regression (MLR). The assumptions of the models were checked after variables were logarithmically transformed except proportions / percentage data (i.e., gradient or land cover), which were transformed using the arcsine of the square root. MLRs were employed in combination with a jackknife procedure (Quenouille, 1949) to obtain an additional (more conservative) r^2 coefficient able to evaluate the predictive ability of the models (i.e.: not only adjusted by the number of cases and variables but also resampled to avoid biases associated with the use of fitted values). Empirical models allowed predicting the selected principal components across the whole drainage network.

Using the predicted synthetic information, a Partitioning Around Medoids (PAM) clustering procedure was used to develop the intended classification in the study area (using between 2 and 20 classes). Previous authors have used this procedure given its robustness (e.g., Snelder et al., 2013). We performed an ANOVA on all the original variables (not the PCA axes) with the class membership as the explanatory variable, in order to analyse the potential of classifications to discriminate them (their performance). The coefficient of determination (r^2) was calculated for each level (2 to 20 class level), with a minimum of five sites per class. Following the procedure outlined in Snelder and Booker (2013) and Snelder et al. (2012), ANOVAs were performed on sites not used in the fitted models by means of a fivefold cross-validation procedure (Hastie et al., 2001). This allowed us to focus on the 'predictive performance' of the classifications. Each cross-validation procedure was repeated 3 times in order to 'smooth' the variability inherent to each subset. Based on the 'one standard error rule', two classifications were assumed significantly different if standard errors of the statistics did not intersect. All analyses were performed in R (R Development Core Team 2015) through the packages 'mclust' (Fraley and Raftery, 2002) and 'vegan' (Oksanen et al., 2016).

3. Results

3.1 Synthetic RHS variables

The first two Principal Components of each PCA explained a 48.5%, 47.9% and 77% of variability for hydromorphologic units, flow types and substrates, respectively. The original RHS variables with the highest loadings on the retained PCs are shown in Table 3. According to the variables with the highest loadings in the PCs, the axes of the PCA developed on hydromorphologic units represented, respectively, (1) the density of hydromorphologic units and (2) the proportion of steps and runs (positive extreme) or cascades and pools (negative extreme; Fig. 2a). The axes of the PCA developed on flow types summarised (1) increased frequencies of non-perceptible and smooth flow regimes and (2) chutes and riffles (Fig. 2b). Finally, the axes of the PCA on substrates represented (1) the size of substrates (with a separation between boulders on one side and cobble, gravel and pebble, on the other) and (2) the presence of bedrock (Fig. 2c). Together with the four variables associated with channel dimensions (bankfull width and depth, on one side, and water width and depth, on the other), these six synthetic axes constituted the set of variables used in the subsequent classification.

3.2 Models and river classification

Model performance, measured by the r^2 coefficient, of the different synthetic variables varied by group (Table 4), tending to be greater in those derived from the first PC than in those derived from the second one. We discarded the second axis of the PCAs based on hydromorphologic units and flow types because of the lack of statistically significant results (Table 4). In general, variables related to topography and river network characteristics were associated with most groups (Table 5). Variables associated with climate also appeared in all groups of variables, but especially flow types (first axis) and channel dimensions. Land cover and geology were only related to hydromorphologic units and channel dimensions. Specifically, the catchment mean precipitation between January and March (MN_minP01_03), total catchment area (MN_AREA), valley floor width (VAL_FLOOR), mean catchment elevation (MN_ELEV) and distance to river outlet (ToOutlet_m) were associated with the density of hydromorphologic units (more variables may be seen in Table 5). Evapotranspiration and temperature (MN_meaE04_09, MN_meaT07_09), together with mean catchment elevation (MN_ELEV) sub-catchment slope (LC_GRAD) and distance to outlet (ToOutlet), were the variables associated with the turbulence of flow types (first flow PCA axis). Hydromorphologic units, substrate types and channel dimensions (particularly, Bankfull Width and Depth) were influenced by catchment forest surface (MN_Bfp) and geological hardness (Mn_hard).

The r^2 values of the classification developed tended to increase as the number of classes was greater (Fig. S1). Taking into consideration such r^2 values and the number of classes necessary to generate them a 6-group classification was selected as the optimum solution (Fig. 3 and Fig. 4). When the discrimination in the physical habitat variables was displayed using boxplots, differences were appreciable among classes (Fig. 4). Class 1 was composed of very short streams (low distances to their outlets) from coastal areas or draining into plateaus with high densities of hydromorphologic units and turbulent flow regimes (Fig. 4a). Class 2 consisted of main streams that supported the lowest density of hydromorphologic units, smooth flow regimes, the finest sediments and the greatest channel dimensions. Class 3 and class 4 were all mountain streams, being those from class 3 slightly smaller, with higher turbulent flows, greater density of hydromorphologic units and larger substrates. Finally, classes 5 and 6 represented a transition from mountain streams to lowland tributaries with sequentially more laminar flow, but also with sequentially more loose sediments and reduced channel dimensions (Fig. 4b).

4. Discussion

This study presents a ‘bottom-up’ predict first then-classify strategy (PredF; see Introduction) to develop a classification based on river physical habitat variables and a high-resolution SNR. The procedure identified meaningful physical classes, as they are based on river reach data instead of on arbitrary boundaries. This procedure could potentially be used for testing hypotheses on the effects that human impacts may have on river channel structure and composition, or in environmental flow studies, as the study of the relationship between hydrology and ecology requires the knowledge of how flow regimes get translated into hydraulic habitats. The application of this classification scheme determined the different role of physical factors that influence river physical habitat characteristics.

4.1 Hydromorphologic patterns in the study area

The sequence of hydromorphologic units, the flow and substrate types and channel dimensions were able to provide clear physical habitat patterns along the rivers and streams in the northern quarter of Spain. The different PCAs revealed that the density of hydromorphologic units, the presence of turbulent or laminar flow regimes and the size of substrates, together with channel dimensions (bankfull and water widths and depths), discriminate river reaches consistently. Similarly, previous studies highlighted the importance of cascade and step-pool channels, as well as plane-bed and pool-riffle streams, to explain geomorphic patterns in streams and rivers (see meta-analysis in Flores et al., 2006). In addition, increasing numbers of steps (typically linked to increasing density of hydromorphologic units) may be associated with different factors and physical characteristics, such as local geologic controls, input of colluvial material (Zimmerman and Church, 2001), local-bed roughness (Curran and Wilcock, 2005), low channel width-to-depth ratios (Grant et al., 1990) and particle size (Chin, 1989).

4.2 Determinants of hydromorphologic variability at varying spatial scales

Most of the geomorphic patterns detected in our study area were successfully associated with environmental variables. Only the second axes of the PCAs based on the sequence of hydromorphologic units and flow types did not show statistically significant associations, and were not used during the classification process. Although this involves a certain potential loss of discretization among similar classes (e.g., mountain streams), the classification still provided sound results. Our results agree with the statement that 'in every respect, the valley rules the stream' (Hynes, 1975), given that environmental variables associated with topography and river network characteristics were the most common in our models. Variables such as catchment area, valley width, sinuosity and slope (topographic variables) may be easily obtained from a DEM or topographic map and compared among study areas. For example, previous studies have indicated that connectivity and proximity of channels to valley walls affect the amount and frequency of colluvial material delivery to channels and that valley characteristics also influence the effectiveness of channel forming events (Costa and O'Connor, 1995; Miller, 1995). In addition, associations between slope gradient and hydromorphologic units have also been described in Northwest Pacific catchments (Montgomery and Buffington, 1998).

Climate, geology and land cover were also related to stream physical characteristics in our study area. The greater importance observed for precipitation, temperature and evapotranspiration was unsurprising given its relevance for stream and river flow regimes (e.g., Snelder & Biggs, 2002; Belmar et al., 2012). They were especially important for flow types, probably because the balance among them determines the runoff generated, and channel dimensions, which may be associated with an incision caused by great volumes of water (a similar effect of such volumes in the context of hydrologic alteration was described by Belmar et al., 2013). The mediation of additional factors, in this case, on the effects produced by climate has been highlighted in the literature (e.g., Poff et al., 2006). For example, lithology and geology have been described to influence local channel morphology as well as stream substrate size (Hack, 1957; Werritty, 1992; Kodama, 1994). Land cover is assumed to influence stream ecosystems through a wide set of processes such as sedimentation, hydrologic alteration, riparian clearing/canopy opening and loss of large woody debris (Allan, 2004). Our study has demonstrated relationships between land cover (i.e., forest surface), on one side, and hydromorphologic units and channel dimensions on the other. In this sense, research has revealed the profound impacts of land cover and land cover changes on sediment yield associated with accelerated watershed-scale soil and river bank erosion (see reviews by Walling, 2004; Gregory, 2006; Wilkinson and McElroy, 2007). Increased sediment supplies from land cover changes due to anthropogenic stress have led to accelerated rates of historical channel narrowing and enhanced channel bed sedimentation (Costa, 1975; Magilligan, 1985; Philips and Gomez; 2007), often degrading channel habitats (Waters, 1995). Nevertheless, the described relationship between forests and river physical habitats may be mediated not only by watershed-scale soil and river bank erosion (and their effects on channel morphology and hydromorphologic units). For example, Belmar et al., (2018) reported that mature forests play an important role in reducing river floods in Atlantic temperate regions, which may also have effects on river physical habitat characteristics.

4.3 Classification of hydromorphologic patterns for water management

The classification scheme implemented in this study provides a useful tool for river management, especially for river restoration, that combines fieldwork and environmental variables integrated in virtual hydrologic networks. The difficulties of restoring habitats (mainly those with minimal human interference) are compounded because, at least in some regions, we still lack single, agreed-upon classification schemes for river types (Elosegi et al., 2011). We propose that these river types may serve as a benchmark condition for habitat assessment and to set river restoration goals and directions for water managers in the context of the ELOHA (Poff et al., 2010) and River Styles (Brierley 1999, Brierley and Fryirs 2000, Thomson et al. 2001, Brierley et al. 2002) frameworks. Since areas subjected to hydrologic alteration will show deviations, physical habitat characterization in sites under anthropogenic pressures may facilitate examination of differences between reference and impacted conditions. Previous studies may help to develop hypotheses. For example, Belmar et al., (2013) demonstrated that, in main streams, releases from big reservoirs (to address irrigation demands) involved not only increased channel dimensions but also homogeneization of aquatic habitats and the absence of in-channel woody debris. Such homogenization reduces the density of hydromorphologic units and the presence of submerged vegetation, which contributes to a reduction in the quality of channel vegetation and banks.

The delineation of river reach classes to whole river networks attending to differences of physical habitat attributes could assist river conservation planning. For example, conservation priorities could be set in order to account for those river classes that have reduced lengths and are subject to greater human impacts (McManamay et al., 2018). Moreover, if the response of fluvial biota to hydraulic changes were similar within each physical habitat class (as expected), the classification might guide the application of environmental flow rules to ungagged river reaches. In this regard, a more effective surveying in the greatest river reaches, which was not possible in our case due to difficulties to access the channel, is advisable to guarantee an optimum training dataset to develop the empirical models. Alternative approaches to estimate physical habitat characteristics such as remote sensing at high resolution (Whited et al., 2002) may result useful. Finally, future research should focus on further validation of physical habitat classes at least in two domains. First, using field observations to verify that the same level of flow in one class may not translate into an important ecological event in another (*sensu* Poff et al., 2006). Second, determining how to evaluate the deviation from reference conditions in sites under anthropogenic pressures. The former will confirm the suitability of physical habitat classes to develop flow alteration-ecological response relationships that reflect the direct and indirect influences of flows on both ecological processes and ecosystem structure and function (Snelder & Biggs, 2002; Jacobson & Galat, 2006; Vaughan et al., 2009). The latter is necessary because the relationship between ecological properties and flow alteration may not be linear (e.g., Bruno et al., 2014) and a proper definition of the physical habitat characteristics and thresholds that allow defining a site as severely impacted results fundamental for water resource management.

5. Contributors

OB performed research, analysed data and wrote the paper. DB and TS contributed to data analysis. FJP and MAC contributed to fieldwork and revised the manuscript. JB conceived the study, performed research and contributed to fieldwork, analyses and writing.

6. Declaration of interests

The authors declare that they have no conflict of interest.

7. Acknowledgements

We wish to thank CEDEX, IGN and IGME for the data provided on hydroclimate, land cover and geology respectively. We also thank *Ecohydros*, *Biotec*, Alfredo Ollero, Daniel Ballarín and Daniel Mora for their contribution to fieldwork, and Ton H. Snelder for his support with data processing.

8. Funding Information

This work was supported by the Ministry for Economy and Competitiveness through funding for the projects 'Development of an Spatial Framework for Integrated Catchment Management (MARCE) [grant number CTM2009-07447]' and 'Effects of Hydrological Alteration on River Functioning and Service Provisioning: Implications for Integrated Catchment Management (HYDRA) [grant number BIA2015-71197]'. Oscar Belmar obtained financial support in an initial stage by means of the Juan de la Cierva [grant number FPDI-2013-16141] program. Francisco J. Peñas is currently supported by Fondos FONDECYT - Concurso postdoctorado (Número de proyecto 3170313).

9. Data availability

The data that support the findings of this study are available from the corresponding author, OB, upon reasonable request.

10. References

ALLAN, J. D. 2004. Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology Evolution and Systematics,* 35**,** 257-284.

ÁLVAREZ-CABRIA, M., BARQUÍN, J. & PEÑAS, F. J. 2016. Modelling the spatial and seasonal variability of water quality for entire river networks: Relationships with natural and anthropogenic factors. *Science of The Total Environment,* 545**,** 152-162.

ÁLVAREZ-CABRIA, M., GONZÁLEZ-FERRERAS, A. M., PEÑAS, F. J. & BARQUÍN, J. 2017. Modelling macroinvertebrate and fish biotic indices: From reaches to entire river networks. *Science of the Total Environment,* 577**,** 308-318.

BAKER, D. W., BLEDSOE, B. P. & PRICE, J. M. 2012. Stream nitrate uptake and transient storage over a gradient of geomorphic complexity, north-central Colorado, USA. *Hydrological Processes,* 26**,** 3241-3252.

BARQUÍN, J., FERNANDEZ, D., ALVAREZ-CABRIA, M. & PEÑAS, F. 2011. Riparian quality and habitat heterogeneity assessment in Cantabrian rivers. *Limnetica,* 30**,** 329-346.

BAXTER, C. V., FRISSELL, C. A. & HAUER, F. R. 1999. Geomorphology, logging roads, and the distribution of bull trout spawning in a forested river basin: Implications for a management and conservation. *Transactions of the American Fisheries Society,* 128**,** 854-867.

BELLETTI, B., RINALDI, M., BUIJSE, A. D., GURNELL, A. M. & MOSSELMAN, E. 2015. A review of assessment methods for river hydromorphology. *Environmental Earth Sciences,* 73**,** 2079-2100.

BELLETTI, B., RINALDI, M., BUSSETTINI, M., COMITI, F., GURNELL, A. M., MAO, L., NARDI, L. & VEZZA, P. 2017. Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units. *Geomorphology,* 283**,** 143-157.

BELMAR, O., BARQUÍN, J., ÁLVAREZ-MARTÍNEZ, J., PEÑAS, F. J. & DEL JESUS, M. 2018. The role of forest maturity on hydrological extreme events. *Ecohydrology,* 2018;11:e1947.

BELMAR, O., BRUNO, D., MARTINEZ-CAPEL, F., BARQUÍN, J. & VELASCO, J. 2013. Effects of flow regime alteration on fluvial habitats and riparian quality in a semiarid Mediterranean basin. *Ecological Indicators,* 30**,** 52-64.

BELMAR, O., VELASCO, J., MARTÍNEZ-CAPEL, F., PEREDO-PARADA, M. & SNELDER, T. 2012. Do Environmental Stream Classifications Support Flow Assessments in Mediterranean Basins? *Water Resources Management,* 26**,** 3803-3817.

BENDA, L., MILLER, D., ANDRAS, K., BIGELOW, P., REEVES, G. & MICHAEL, D. 2007. NetMap: A new tool in support of watershed science and resource management. *Forest Science,* 53**,** 206-219.

BRIERLEY, G. 1999. River styles: An integrative biophysical template for river management. *In:* RUTHERFORD, I. & BARTLEY, R. (eds.) *Proceedings of the Second Australian Stream Management Conference: The Challenge of Rehabilitating Australia's Streams* (Vol 1). Cooperative Research Centre for Catchment Hydrology, Adelaide, Australia.

BRIERLEY, G. J. & FRYIRS, K. 2000. River styles, a geomorphic approach to catchment characterization: Implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environmental Management,* 25**,** 661-679.

BRIERLEY, G. J. & FRYIRS, K. 2002. *The River Styles Framework: The Short Course Conceptual Book.* Macquarie Lighthouse Press, Sydney, Australia.

BRUNO, D., BELMAR, O., SANCHEZ-FERNANDEZ, D., GUARESCHI, S., MILLAN, A. & VELASCO, J. 2014. Responses of Mediterranean aquatic and riparian communities to human pressures at different spatial scales. *Ecological Indicators,* 45**,** 456-464.

CHIN, A. 1989. Step Pools in Stream Channels. *Progress in Physical Geography,* 13**,** 390-407.

CLINTON, D., JENNINGS, G., HARMAN, W., PATTERSON, J., O' HARA, L. & WILLIAMS, J. 1999. North Carolina reference stream channel morphology relationships. *Wildland Hydrology, Proceedings*, 393-400.

COSTA, J. E. 1975. Effects of Agriculture on Erosion and Sedimentation in Piedmont Province, Maryland. *Geological Society of America Bulletin,* 86**,** 1281-1286.

COSTA, J. E. & O'CONNOR, J. E. 1995. Geomorphically effective floods. *In:* COSTA, J. E. E. A. (ed.) *Natural and Anthropogenic Influences in Fluvial Geomorphology, Geophys. Monogr. Ser., vol. 89.* Washington, D. C.: AGU.

CURRAN, J. C. & WILCOCK, P. R. 2005. Characteristic dimensions of the step-pool bed configuration: An experimental study. *Water Resources Research,* 41.

ELOSEGI, A., FLORES, L. & DIEZ, J. 2011. The importance of local processes on river habitat characteristics: A Basque stream case study. *Limnetica,* 30**,** 183-196.

AGENCY, E. 2003. *River Habitat Survey in Britain and Ireland. Field Survey Guidance Manual,* Bristol, Environment Agency.

DORMANN, C.F., ELITH, J., BACHER, S., BUCHMANN, C., CARL, G., CARRÉ, G., GARCÍA MARQUÉZ, J.R., GRUBER, B., LAFOURCADE, B., LEITÃO, P.J., MÜNKEMÜLLER, T., MCCLEAN, C., OSBORNE, P.E., REINEKING, B., SCHRÖDER, B., SKIDMORE, A.K., ZURELL, D. & LAUTENBACH, S. (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography*, 36, 27–46.

ESTRELA, T., CABEZAS, F. & ESTRADA, F. 1999. La evaluación de los recursos hídricos en el Libro Blanco del Agua en España. *Ingeniería del Agua,* 6**,** 125–138.

FERNANDEZ, D., BARQUIN, J. & RAVEN, P. J. 2011. A review of river habitat characterisation methods: indices vs. characterisation protocols. *Limnetica,* 30**,** 217-234.

FERRIER, S. & GUISAN, A. 2006. Spatial modelling of biodiversity at the community level. *Journal of Applied Ecology,* 43**,** 393-404.

FLORES, A. N., BLEDSOE, B. P., CUHACIYAN, C. O. & WOHL, E. E. 2006. Channel-reach morphology dependence on energy, scale, and hydroclimatic processes with implications for prediction using geospatial data. *Water Resources Research,* 42.

FRALEY, C. & RAFTERY, A. E. 2002. Model-based Clustering, Discriminant Analysis and Density Estimation. *Journal of the American Statistical Association,* 97**,** 611-631.

GRANT, G. E., SWANSON, F. J. & WOLMAN, M. G. 1990. Pattern and Origin of Stepped-Bed Morphology in High-Gradient Streams, Western Cascades, Oregon. *Geological Society of America Bulletin,* 102**,** 340-352.

GREGORY, K. J. 2006. The human role in changing river channels. *Geomorphology,* 79**,** 172-191.

HACK, J. T. 1957. *Studies of longitudinal stream profiles in Virginia and Maryland, U.S. Geol. Surv. Prof. Pap., 294–B, 45–97*.

HARRELSON, C. C., RAWLINS, C. L. & POTYONDY, J. P. 1994. *Stream Channel Reference Sites: An Illustrated Guide to Field Technique. Forest Service General Technical Report RM-245,* Fort Collins, Colorado, U.S. Department of Agriculture.

HASTIE, L. C., COOKSLEY, S. L., SCOUGALL, F., YOUNG, M. R., BOON, P. J. & GAYWOOD, M. J. 2003. Characterization of freshwater pearl mussel (Margaritifera margaritifera) riverine habitat using River Habitat Survey data. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 13**,** 213-224.

HASTIE, T., TIBSHIRANI, R. & FRIEDMAN, J. H. 2001. *The Elements of Statistical Learning: Data Mining, Inference, and Prediction,* New York, Springer-Verlag.

HAWKINS, C. P., KERSHNER, J. L., BISSON, P. A., BRYANT, M. D., DECKER, L. M., GREGORY, S. V., MCCULLOUGH, D. A., OVERTON, C. K., REEVES, G. H., STEEDMAN, R. J. & YOUNG, M. K. 1993. A Hierarchical Approach to Classifying Stream Habitat Features. *Fisheries,* 18**,** 3-12.

HYNES, H. B. N. 1975. The stream and its valley. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie,* 19**,** 1-15.

IHCANTABRIA. 2012. *MARCE Project* [Online]. IH Cantabria. Available: http://www.ihcantabria.com/es/proyectos-id/item/369-desarrollo-de-un-marco-espacial-para-la-gestion-integrada-decuenca-marce [Accessed Nov. 2018].

JACOBSON, R. B. & GALAT, D. L. 2006. Flow and form in rehabilitation of large-river ecosystems: An example from the Lower Missouri River. *Geomorphology,* 77**,** 249-269.

JURACEK, K. E. & FITZPATRICK, F. A. 2003. Limitations and implications of stream classification. *Journal of the American Water Resources Association,* 39**,** 659-670.

KENNARD, M. J., PUSEY, B. J., OLDEN, J. D., MACKAY, S. J., STEIN, J. L. & MARSH, N. 2010. Classification of natural flow regimes in Australia to support environmental flow management. *Freshwater Biology,* 55**,** 171-193.

KENNEN, J. G., KAUFFMAN, L. J., AYERS, M. A., WOLOCK, D. M. & COLARULLO, S. J. 2008. Use of an integrated flow model to estimate ecologically relevant hydrologic characteristics at stream biomonitoring sites. *Ecological Modelling,* 211**,** 57-76.

KODAMA, Y. 1994. Downstream Changes in the Lithology and Grain-Size of Fluvial Gravels, the Watarase River, Japan - Evidence of the Role of Abrasion in Downstream Fining. *Journal of Sedimentary Research Section a-Sedimentary Petrology and Processes,* 64**,** 68-75.

LIERMANN, C. A. R., OLDEN, J. D., BEECHIE, T. J., KENNARD, M. J., SKIDMORE, P. B., KONRAD, C. P. & IMAKI, H. 2012. Hydrogeomorphic Classification of Washington State Rivers to Support

Emerging Environmental Flow Management Strategies. *River Research and Applications,* 28**,** 1340-1358.

MACKEY, B. G., BERRY, S. L. & BROWN, T. 2008. Reconciling approaches to biogeographical regionalization: a systematic and generic framework examined with a case study of the Australian continent. *Journal of Biogeography,* 35**,** 213-229.

MAGILLIGAN, F. J. 1985. Historical Floodplain Sedimentation in the Galena River Basin, Wisconsin and Illinois. *Annals of the Association of American Geographers,* 75**,** 583-594.

MANEL, S., BUCKTON, S. T. & ORMEROD, S. J. 2000. Testing large-scale hypotheses using surveys: the effects of land use on the habitats, invertebrates and birds of Himalayan rivers. *Journal of Applied Ecology,* 37**,** 756-770.

MC GINNITY, P., MILLS, P., ROCHE, W. & MULLES, M. 2005. *Water Framework Directive: A Desk Study to Determine a Methodology for the Monitoring of the 'Morphological Condition' of Irish Rivers for the Water Framework Directive (2002-W-DS-9-M1),* Wexford (Ireland), Environmental Protection Agency.

MCMANAMAY, R. A., TROIA, M. J., DEROLPH, C. R., SHELDON, A. O., BARNETT, A. R., KAO, S.-C. & ANDERSON, M. G. 2018. A stream classification system to explore the physical habitat diversity and anthropogenic impacts in riverscapes of the eastern United States. *PloS one,* 13**,** e0198439.

MILLER, A. J. 1995. Valley morphology and boundary conditions influencing spatial patterns of flood flow, in Natural and Anthropogenic Influences in Fluvial Geomorphology. *In:* COSTA, J. E. E. A. (ed.) *Geophysical Monograph Series.* Washington, D. C.

MONTGOMERY, D. R. & BUFFINGTON, J. M. 1993. *Channel classification, prediction of channel response, and assessment of channel condition*, University of Washington.

MONTGOMERY, D. R. & BUFFINGTON, J. M. 1998. Channel Processes, Classification and Response. *In:* NAIMAN, R. J. & BILBY, R. (eds.) *River Ecology and Management.* New York: Springer-Verlag.

MYERS, T. J. & SWANSON, S. 1992. Variation of Stream Stability with Stream Type and Livestock Bank Damage in Northern Nevada. *Water Resources Bulletin,* 28**,** 743-754.

NAURA, M., CLARK, M. J., SEAR, D. A., ATKINSON, P. M., HORNBY, D. D., KEMP, P., ENGLAND, J., PEIRSON, G., BROMLEY, C. & CARTER, M. G. 2016. Mapping habitat indices across river networks using spatial statistical modelling of River Habitat Survey data. *Ecological Indicators,* 66**,** 20-29.

O'KEEFE, J. H. & UYS, M. C. 2000. The role of classification the conservation of rivers. *In:* BOON, P. J., DAVIES, B. R. & PETTS, G. E. (eds.) *Global perspectives on river conservation: Science policy and practice.* Chichester: John Wiley & Sons.

OGDAHL, M. E., LOUGHEED, V. L., STEVENSON, R. J. & STEINMAN, A. D. 2010. Influences of Multi-Scale Habitat on Metabolism in a Coastal Great Lakes Watershed. *Ecosystems,* 13**,** 222-238.

OKSANEN, J., GUILLAUME-BLANCHET, F., KINDT, R., LEGENDRE, P., MINCHIN, P. R., O'HARA, R. B., SIMPSON, G. L., SOLYMOS, P., STEVENS, M. H. H. & WAGNER, H. 2016. vegan: Community Ecology Package. R package version 2.3-5.

OLDEN, J. D., KENNARD, M. J. & PUSEY, B. J. 2012. A framework for hydrologic classification with a review of methodologies and applications in ecohydrology. *Ecohydrology,* 5**,** 503-518.

PARSONS, M., THOMS, M. C. & NORRIS, R. H. 2003. Scales of macroinvertebrate distribution in relation to the hierarchical organization of river systems. *Journal of the North American Benthological Society,* 22**,** 105-122.

PEÑAS, F. J., BARQUÍN, J. & ÁLVAREZ, C. 2018. A comparison of modeling techniques to predict hydrological indices in ungauged rivers. *Limnetica,* 37**,** 145-158.

PEÑAS, F. J., BARQUÍN, J., SNELDER, T. H., BOOKER, D. J. & ALVAREZ, C. 2014. The influence of methodological procedures on hydrological classification performance. *Hydrology and Earth System Sciences,* 18**,** 3393-3409.

PHILLIPS, J. D. & GOMEZ, B. 2007. Controls on sediment export from the Waipaoa River basin, New Zealand. *Basin Research,* 19**,** 241-252.

POFF, N. L., OLDEN, J. D., PEPIN, D. M. & BLEDSOE, B. P. 2006. Placing global stream flow variability in geographic and geomorphic contexts. *River Research and Applications,* 22**,** 149-166.

POFF, N. L., RICHTER, B. D., ARTHINGTON, A. H., BUNN, S. E., NAIMAN, R. J., KENDY, E., ACREMAN, M., APSE, C., BLEDSOE, B. P., FREEMAN, M. C., HENRIKSEN, J., JACOBSON, R. B., KENNEN, J. G., MERRITT, D. M., O'KEEFFE, J. H., OLDEN, J. D., ROGERS, K., THARME, R. E. & WARNER, A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology,* 55**,** 147-170.

QUENOUILLE, M. H. 1949. Problems in plane sampling. *The Annals of Mathematical Statistics,* 20**,** 355-375.

R CORE TEAM. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna (Austria).

RAVEN, P. J., FOX, P., EVERARD, M., HOLMES, N. T. H. & DAWSON, F. H. 1997. River habitat survey: A new system for classifying rivers according to their habitat quality. *Freshwater Quality: Defining the Indefinable?***,** 215-234.

RAVEN, P. J., HOLMES, N. T. H., DAWSON, F. H. & EVERARD, M. 1998. Quality assessment using River Habitat Survey data. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 8**,** 477-499.

RAVEN, P. J., HOLMES, N. T. H., VAUGHAN, I. P., DAWSON, F. H. & SCARLETT, P. 2010. Benchmarking habitat quality: observations using River Habitat Survey on near-natural streams and rivers in northern and western Europe. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 20, S13-S30.

RIVAS-MARTÍNEZ, S., PEÑAS, A. & DÍAZ, T. E. 2004. *Bioclimatic Map of Europe, Bioclimates,* León, Spain, Cartographic Service, University of León.

ROSGEN, D. L. 1985. A Stream Classification System. *Riparian Ecosystems and Their Management. Proceedings of the First North American Riparian Conference, April 16-18, Tucson, Arizona. USDA Forest Service General Technical Report No. RM-120.*

ROSGEN, D. L. 1994. A Classification of Natural Rivers. *Catena,* 22, 169-199.

ROSGEN, D. L. 1996. *Applied River Morphology,* Pagosa Springs, Colorado, Wildland Hydrology.

SMITH, R. L. 1990. *Ecology and field biology,* New York, Harper Collins.

SNELDER, T., ORTIZ, J. B., BOOKER, D., LAMOUROUX, N., PELLA, H. & SHANKAR, U. 2012. Can bottom-up procedures improve the performance of stream classifications? *Aquatic sciences,* 74, 45-59.

SNELDER, T. H. & BIGGS, B. J. F. 2002. Multiscale River Environment Classification for water resources management. *Journal of the American Water Resources Association,* 38, 1225-1239.

SNELDER, T. H., BIGGS, B. J. F. & WOODS, R. A. 2005. Improved eco-hydrological classification of rivers. *River Research and Applications,* 21, 609-628.

SNELDER, T. H. & BOOKER, D. J. 2013. Natural Flow Regime Classifications Are Sensitive to Definition Procedures. *River Research and Applications,* 29, 822-838.

SNELDER, T. H., LAMOUROUX, N., LEATHWICK, J. R., PELLA, H., SAUQUET, E. & SHANKAR, U. 2009. Predictive mapping of the natural flow regimes of France. *Journal of Hydrology,* 373, 57-67.

SNELDER, T. H., PELLA, H., WASSON, J. G. & LAMOUROUX, N. 2008. Definition Procedures Have Little Effect on Performance of Environmental Classifications of Streams and Rivers. *Environmental Management,* 42, 771-788.

STEIN, J. L., HUTCHINSON, M. F., PUSEY, B. J. & KENNARD, M. J. 2009. Ecohydrological classification based on landscape and climate data. Appendix 8. *In:* PUSEY, B. J., KENNARD, M. J., STEIN, J. L., OLDEN, J. D., MACKAY, S. J., HUTCHINSON, M. F. & SHELDON, F. (eds.) *Ecohydrological Regionalisation of Australia: A Tool for Management and Science. Innovations Project GRU36, Final Report to Land and Water Australia.*

THOMSON, J. R., TAYLOR, M. P., FRYIRS, K. A. & BRIERLEY, G. J. 2001. A geomorphological framework for river characterization and habitat assessment. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 11**,** 373-389.

VAUGHAN, I. P., DIAMOND, M., GURNELL, A. M., HALL, K. A., JENKINS, A., MILNER, N. J., NAYLOR, L. A., SEAR, D. A., WOODWARD, G. & ORMEROD, S. J. 2009. Integrating ecology with hydromorphology: a priority for river science and management. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 19**,** 113-125.

VAUGHAN, I. P., MERRIX-JONES, F. L. & CONSTANTINE, J. A. 2013. Successful predictions of river characteristics across England and Wales based on ordination. *Geomorphology,* 194**,** 121-131.

VAUGHAN, I. P., NOBLE, D. G. & ORMEROD, S. J. 2007. Combining surveys of river habitats and river birds to appraise riverine hydromorphology. *Freshwater Biology,* 52**,** 2270-2284.

WALKER, J., DIAMOND, M. & NAURA, M. 2002. The development of Physical Quality Objectives for rivers in England and Wales. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 12**,** 381-390.

WALLLING, D. 2004. *Using Environmental Radionuclides to Trace Sediment Mobilisation and Delivery in River Basins as an Aid to Catchment Management. Proceedings of the Ninth International Symposium on River Sedimentation, 18–21 October 2004, Yichang, China,* Beijing, China, Tsinghua University Press.

WALTERS, D. M., LEIGH, D. S., FREEMAN, M. C., FREEMAN, B. J. & PRINGLE, C. M. 2003. Geomorphology and fish assemblages in a Piedmont river basin, USA. *Freshwater Biology,* 48**,** 1950-1970.

WATERS, T. 1995. *Sediment in Streams: Sources, Biological Effects, and Control. American Fisheries Society Monograph, Bethesda, MD*.

WERRITTY, A. 1992. Downstream fining in a gravel-bed river in southern Poland: Lithologic controls and the role of abrasion. *In:* BILLI, P. E. A. (ed.) *Dynamics of Gravel-Bed Rivers.* Hoboken, N. J.: John Wiley.

WHITED, D., STANFORD, J. AND KIMBALL, J. 2002. Application of airborne multispectral digital imagery to quantify riverine habitats at different base flows. *River Research and Applications*, 18(6), 583-594.

WILKINSON, B. H. & MCELROY, B. J. 2007. The impact of humans on continental erosion and sedimentation. *Geological Society of America Bulletin,* 119**,** 140-156.

ZIMMERMANN, A. & CHURCH, M. 2001. Channel morphology, gradient profiles and bed stresses during flood in a step-pool channel. *Geomorphology,* 40**,** 311-327.

Table 1. Variables (SQ: Semiquantitative; Q: Quantitative), organized by groups, derived from the River Habitat Survey to characterize physical habitat in the streams and rivers of the northern quarter of Spain (and run the corresponding Principal Component Analyses).

Group	Variable	Meaning	Characterisation of the habitat feature
Sequence of	CA	Cascade	High channel gradient which constitutes at least a drop of one meter. Fast flows are present and the spatial distribution is heterogeneous
hydro-	PO	Pool	Distinctly deeper parts of the channel where the hollowed river bed profiles are sustained by scouring
morphologic	TF	Trench Flow	Channel incised and flanked by bedrock walls with uniform unidirectional fast flow over the whole channel width
units	GL	Glide	Unidirectional smooth or no perceptible flow over the whole channel width
	RU	Run	Flow is not homogeneous, presenting occasional and minor turbulences
(SQ)	RA	Rapid	Highly turbulent flow over unconsolidated substrate
	RI	Riffle	Fast-flowing water with a distinctly disturbed surface over unconsolidated substrate
	ST	Step	Reduced dimensions when comparing with surrounding habitats. It always constitutes a break, separating two habitats
	WA	Waterfall	Big step (at least 1 meter) with no interruptions in the fall and which prevent fish to go upriver
Flow types	BW	Broken standing waves	White-water tumbling waves must be present
	UW	Unbroken standing waves	Upstream facing wavelets which are not broken
(SQ)	RP	Rippled	No waves, but general flow direction is downstream with disturbed rippled surface
	CH	Chute	Low curving fall in contact with substrate
	SM	Smooth	Perceptible downstream movement is smooth (no eddies)
	NP	No perceptible flow	No net downstream flow
Substrates	BE	Bedrock	Underlying solid rock
	BO	Boulder	Large rocks > 256 mm in diameter (larger than head size)
(SQ)	CO	Cobble	Loose material 64-256 mm in diameter (half-fist to large head size)
	GP	Gravel/pebble	Combined category: Coarse gravel is 16-64 mm in diameter (includes pebbles that are conker to half-fist size); fine gravel is 2-16 mm in diameter
Channel	BH	Bankfull height	Vertical distance from riverbed, to the first major break in slope above which cultivation or development is possible (estimated from sweep-up)
dimensions	BW	Bankfull width	Horizontal distance across the channel to be measured at the level where the river first spills on to the floodplain (estimated from sweep-up)
(Q)	WD	Water depth	Maximum depth in the wetted channel (averaged across ten spot-checks)
	WW	Water width	Distance across the wetted perimeter of the channel (averaged across ten spot-checks)

Table 2. Environmental predictor variables used in the corresponding Multiple Linear Regressions of physical habitat characteristics in the study area. Note that, in general, they were computed at catchment (MN), sub-catchment (LC) and reach scales (BF).

Factor	Variable	Meaning
Topography	MN_AREA	Total catchment area
	VAL_FLOOR	Valley floor width
	MN_GRAD	Catchment slope
	LC_GRAD	Sub-catchment slope
	MN_ELEV	Catchment elevation
River network characteristics	ToOutlet_m	Distance from segment to river mouth
	SINUOSITY	River reach sinuosity
Climate	MN_maxP10_03	Catchment maximum precipitation (October - March)
	MN_minP01_03	Catchment minimum precipitation (January - March)
	MN_minP07_09	Catchment minimum precipitation (July - September)
	MN_meaE04_09	Catchment mean evapotranspiration (April - September)
	MN_meaT07_09	Catchment mean temperature (July - September)
Land cover	MN_Bfp	Catchment broad leaf forest area
	LC_Bfp	Sub-catchment broad leaf forest area
	BF_Bfp	Reach broad leaf forest area
	MN_SS	Catchment scrubs and shrubs area
	LC_SS	Sub-catchment scrubs and shrubs area
	BF_SS	Reach scrubs and shrubs area
Geology	MN_Hard	Catchment rock hardness
	LC_Hard	Sub-catchment rock hardness
	BF_Hard	Reach rock hardness

Table 3. Factor loadings of the first two axes of the Principal Component Analyses (PCA) performed for hydromorphologic units (HMUs), flow types and substrate types (channel dimensions were not introduced in any PCA) obtained using a modified version of the River Habitat Survey protocol in rivers from the northern quarter of Spain.

Variable	**Meaning**	**PC1**	**PC2**
Dens_PO	Pool density	0.35	-0.26
Dens_ST	Step density	0.38	0.27
Dens_RU	Run density	0.32	0.36
Dens_GL	Glide density	-0.07	-0.07
Dens_CA	Cascade density	0.32	-0.23
Dens_RA	Rapid density	-0.04	-0.06
Dens_RI	Riffle density	0.05	-0.15
Dens_nHMUsTypes	Density of types of HMU	0.27	-0.13
DensHMUs	Density of HMUs	0.43	0.06
Rel_PO	Pool proportion	0.21	-0.40
Rel_ST	Step proportion	0.25	0.37
Rel_RU	Run proportion	-0.08	0.46
Rel_GL	Glide proportion	-0.24	-0.07
Rel_CA	Cascade proportion	0.22	-0.28
Rel_RA	Rapid proportion	-0.18	-0.12
Rel_RI	Riffle proportion	-0.09	-0.15
CH	Chute	-0.16	0.47
BW	Broken standing waves	-0.59	-0.46
UW	Unbroken standing waves	-0.18	-0.19
RP	Rippled	-0.12	0.71
SM	Smooth	0.64	-0.12
NP	No perceptible flow	0.42	-0.16
BE	Bedrock	0.10	-0.88
BO	Boulder	0.66	0.40
CO	Cobble	-0.57	0.23
GP	Gravel/pebble	-0.48	0.08
BH	Bankfull height	-	-
BW	Bankfull width	-	-
WD	Water depth	-	-
WW	Water width	-	-

Table 4. Multiple Linear Models (MLR; r^2 values, with and without jackknife procedure) on synthetic habitat variables using environmental variables ('*' denotes statistically significant p-value; <0.05).

Group of variables	Habitat variable	Meaning	r^2	r^2 (jackknife)
Sequence of hydro-morphologic units	HPCA1	First PCA axis	0.47*	0.40*
	HPCA2	Second PCA axis	0.07	0.01
Flow types	FPCA1	First PCA axis	0.38*	0.27*
	FPCA2	Second PCA axis	0.09	0.02
Substrates	SPCA1	First PCA axis	0.20*	0.14*
	SPCA2	Second PCA axis	0.17*	0.06*
Channel dimensions	BW	Bankfull width	0.45*	0.34*
	BH	Bankfull height	0.43*	0.23*
	WW	Water width	0.48*	0.35*
	WD	Water depth	0.63*	0.55*

Table 5. Most important environmental variables significantly explaining the synthetic habitat variables (see Table 4) according to Multiple Linear Regression (MRL). HPCA: hydromorphologic units; FPCA: flow-types; SPCA: substrates; bankfull width: BW; bankfull height: BH; water width: WW; water depth: WD. 'MN' and 'LC' indicate if they were computed at catchment and sub-catchment scale, respectively.

Factor	**Variable**	**Meaning**	**HPCA1**	**FPCA1**	**SPCA1**	**SPCA2**	**BW**	**BH**	**WW**	**WD**
Topography	MN_AREA	Total catchment area	X		X		X	X	X	X
	VAL_FLOOR	Valley floor width	X			X		X	X	
	MN_GRAD	Catchment slope	X							
	LC_GRAD	Sub-catchment slope		X		X			X	
	MN_ELEV	Catchment elevation	X	X		X	X	X	X	X
River network characteristics	ToOutlet_m	Distance from segment to river mouth	X	X		X		X		
	SINUOSITY	River reach sinuosity						X		X
Climate	MN_maxP10_03	Catchment maximum precipitation (October - March)					X		X	X
	MN_minP01_03	Catchment minimum precipitation (January - March)	X				X	X	X	X
	MN_minP07_09	Catchment minimum precipitation (July - September)								
	MN_meaE04_09	Catchment mean evapotranspiration (April - September)		X	X			X		X
	MN_meaT07_09	Catchment mean temperature (July - September)		X					X	
Land cover	MN_Bfp	Catchment broad leaf forest area	X					X		
	LC_Bfp	Sub-catchment broad leaf forest area								
	BF_Bfp	Reach broad leaf forest area								
	MN_SS	Catchment scrubs and shrubs area								
	LC_SS	Sub-catchment scrubs and shrubs area								
	BF_SS	Reach scrubs and shrubs area								
Geology	MN_Hard	Catchment rock hardness	X				X			
	LC_Hard	Sub-catchment rock hardness								
	BF_Hard	Reach rock hardness	X							

Figure S1. R^2 values (5-fold ANOVA) for an increasing classification level (number of classes) using standardized synthetic habitat variables: (a) hydromorphologic units, (b) flow types, (c) substrates and (d) channel dimensions, respectively (variable meaning in Table 3). Only cases with a minimum of five sites are showed. Given its greater number, some hydromorphologic units are not represented.

(a)

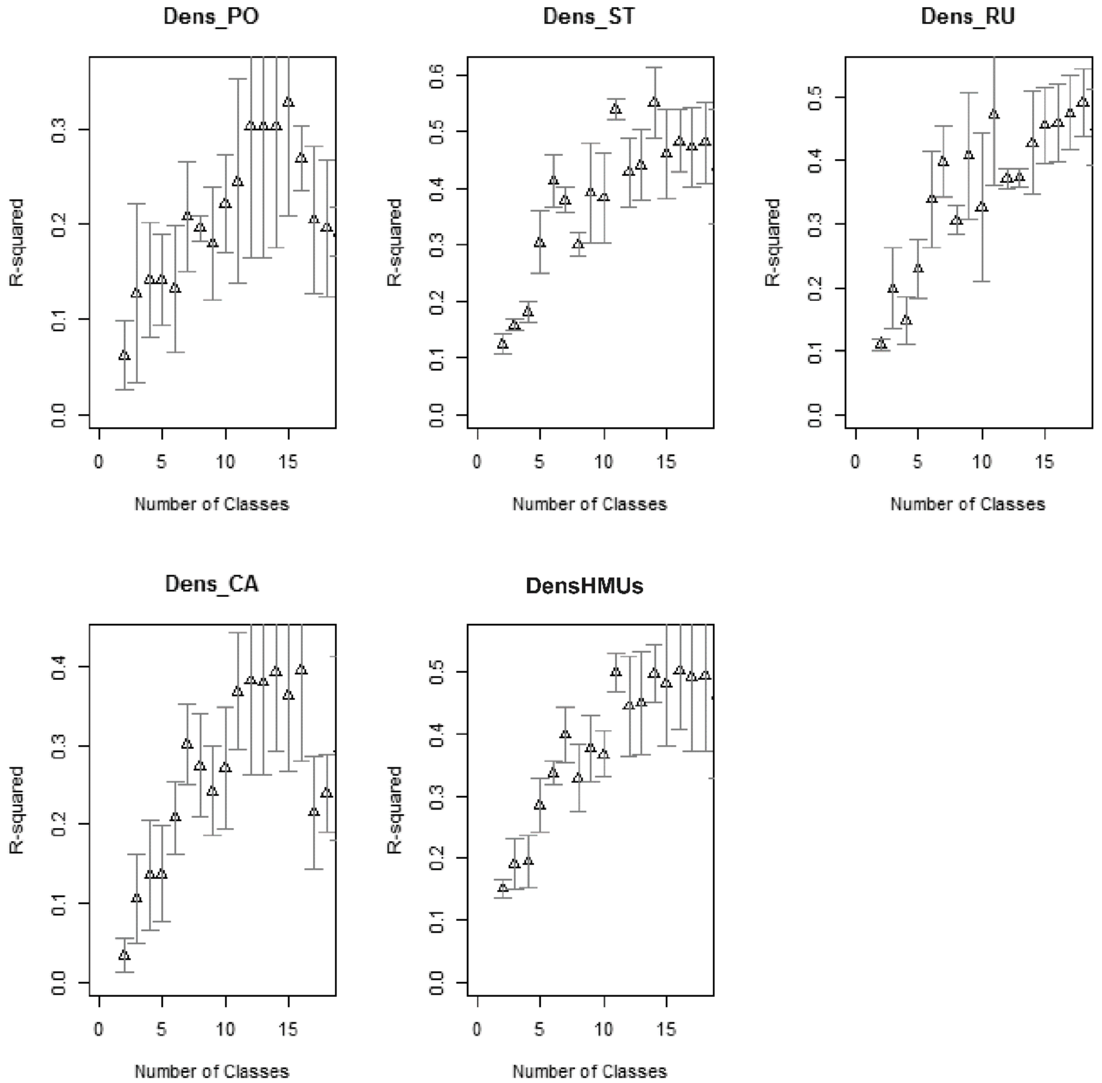
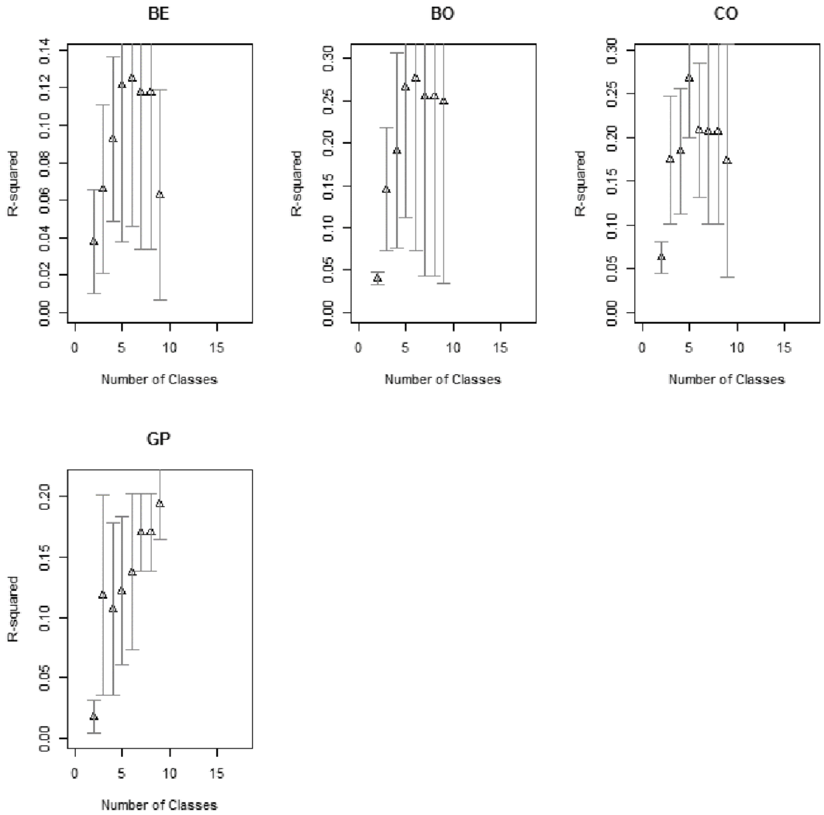


Figure S1 (cont.)

(b)



(c)

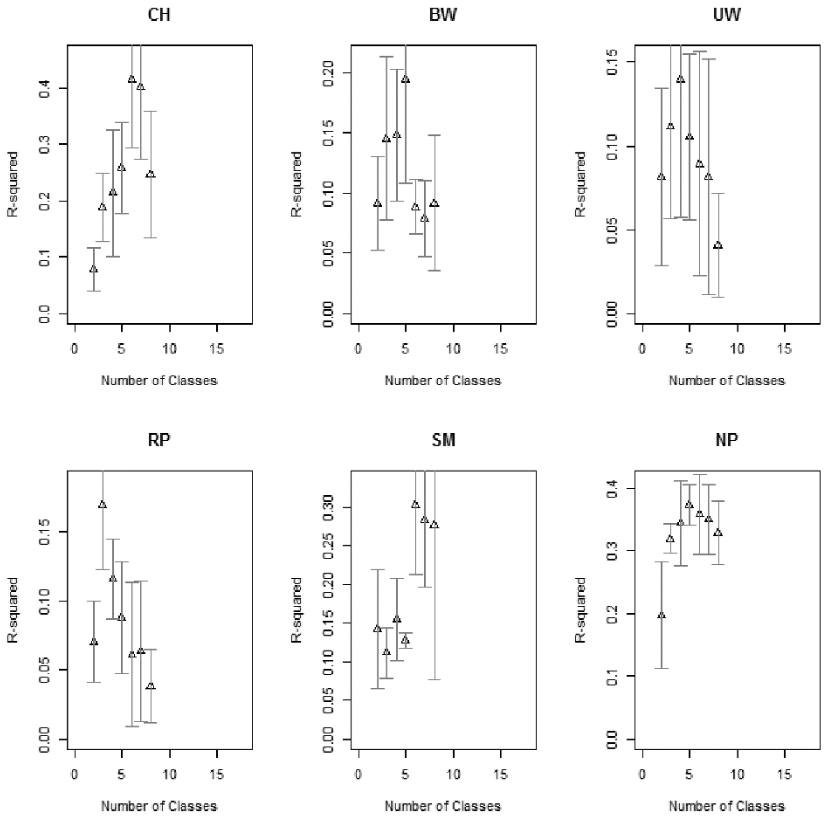


Figure S1 (cont.)

(d)

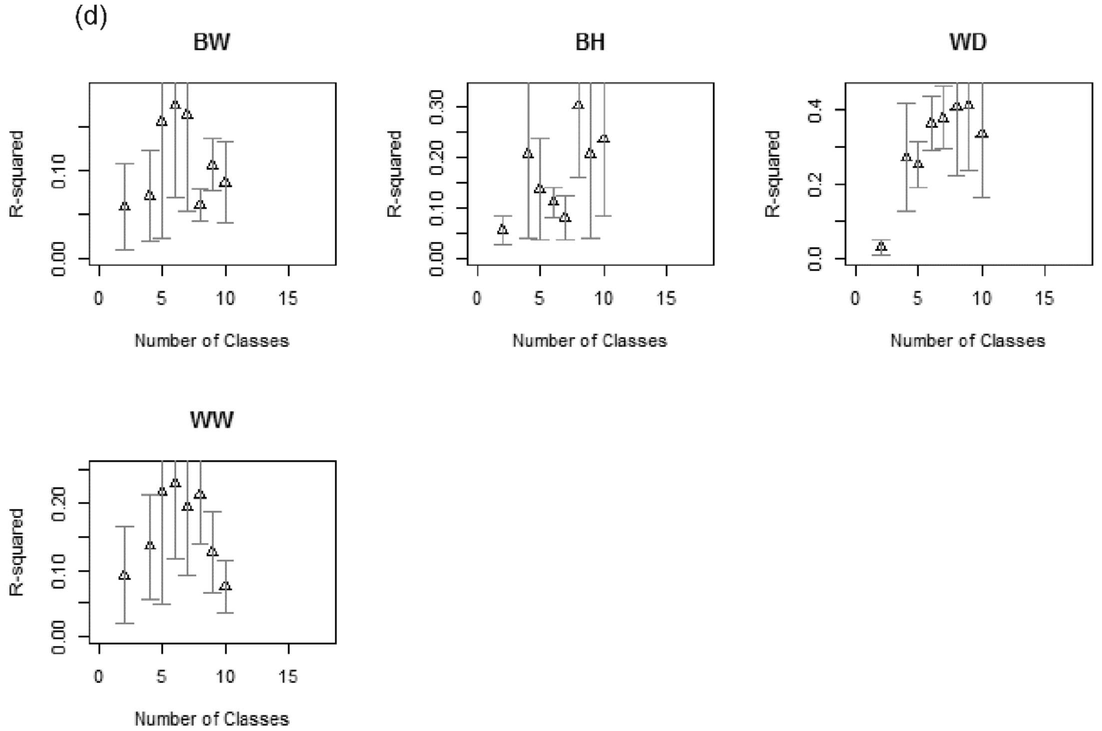


Figure legend list

Figure 1. Drainage network of the northern quarter of Spain, which encompasses three water basins (Cantabrian, Ebro and Catalan). Surveyed river reaches (through River Habitat Survey) are shown as points (the black ones were discarded because they did not fulfil the criteria for analyses; see Methods).

Figure 2. Principal Component Analyses (PCAs) of hydromorphologic units, flow types and substrates to derive synthetic variables from their axes (variable meaning in Table 3).

Figure 3. Hydromorphologic classification using standardized synthetic habitat variables on a high resolution Synthetic River Network (SRN).

Figure 4. Between-class differences on: (a) synthetic RHS variables for the classification developed and (b) channel dimensions. HPCA: hydromorphologic units; FTPCA: flow types; STPCA: substrates, BW: bankfull width; BH: bankfull height; WD: water depth; WW: water width. Vertical axes labelled to facilitate interpretation (the second axis for flow types and hydromorphologic units is not represented due to the lack of statistically significant values in linear models).