Original Articles

Application of ~~Lithotopo Units For Automatic Classification of Rivers: Concept, Development and V~~lithotopo units for automatic classification of rivers: Concept, development and validation

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~~Bloque ACampus Universitario SurSantiago de CompostelaCompostela15782Spain~~Abstract

River classification is one of the recommendations of the European Water Framework Directive 2000/60/EC, which establishes that classifications should be carried out according to different variables hierarchically organized from a smaller to a larger scale. We suggest incorporating into the Directive’s hierarchical system a geoecological unit (lithotopo unit) that discriminates rivers with similar geomorphological features and ecological funtionality. The lithotopo units are not an alternative to the Directive typology, they are a complement intended to improve it.

Our method is divided into two stages, the first focused on the development of LTUs and the second on their validation. We applied the concept of lithotopo units to a 30,000 km^2 region in the NW of the Iberian Peninsula (Spain) using a Geographic Information System and field work. Seven kinds of lithotopo units were identified for the study area, each with its own geomorphological processes and dynamics, and, as a consequence, particular associated habitats. Cartographic validation was done through the analysis of 122 sample sites distributed in eight basins. Of the five validation variables originally employed, specific stream power and median grain size are the two that yielded the best results. Each kind of lithotopo unit displays a range of values of specific stream power and median grain size that is internally homogeneous but different from that of the other units. The methodology thus produced, which can be applied to other regions, is transparent, objective and quantitative.

Keywords: Lithotopo unit; Geoecology; Water Framework Directive 2000/60/EC; Fluvial geomorphology; Classification system

1 I~~NTRODUCTION~~ntroduction

Fluvial systems are formed by a wide range of elements with multiple non-linear interactions on different spatial and temporal scales (Knighton, 1998; Rice et al., 2010a; Wheaton et al., 2011; Stoffel et al., 2013). The geomorphological elements of a river system (Newson, 2002; Blue and Brierley, 2015) are key influences on the biological component that often motivates fluvial assessment and restoration (Frissell et al., 1986; Palmer et al., 2010).

Fluvial geomorphology processes drive the creation and development of habitats and control ecological processes, and are thus fundamental to the quality of the fluvial ecosystem (Newson and Large, 2006; Vaughan et al., 2009). Therefore, an ecological understanding of fluvial systems requires a solid understanding of its geomorphological dimensions (Fryirs and Brierley, 2012).

In many countries, recent decades have witnessed important changes in environmental law and policy as a result of fluvial conservation and restoration initiatives (Kondolf and Micheli, 1995; Poff et al., 2003; Rohde, 2004; Wohl et al., 2005; González del Tánago and García de Jalón, 2007; Palmer et al., 2007; Brierley and Fryirs, 2008; Magdaleno, 2008; Beechie et al., 2010; González Briz et al., 2015). In Europe these changes led to several influential regulations, including Habitats Directive 92/43/EC, Water Framework Directive 2000/60/EC (henceforth WFD), Floods Directive 2007/60/EC, and Environmental Quality Standards Directive 2008/105/EC. The WFD proposes river classification as one of its recommendations to help improve the ecological status of river systems. This takes into account different variables and features in a hierarchical organization from smaller to larger scale, and facilitates the establishment of reference conditions for each river type. The WFD suggests two systems of characterization (A and B) based on different variables or features. System A, which is obligatory, is intended to locate the river within its biogeographical setting. It includes variables related to basin level hydrological processes to establish a common regional European typology. System B includes additional optional factors in order to further characterize rivers on different spatial scales.

The WFD recognizes that geomorphological principles are vital for river ecology. However, the proposed hydrogeomorphological variables are optional and insufficient (Ollero et al., 2003). Article 4 of the WFD states that Member States should: “*achieve good surface water status at the latest 15 years after the date of entry into force of this Directive*”. Now, after 15 years under the Directive, this goal has not been fulfilled in many European rivers. We believe that this is, in part, due to (i) lack of involvement of geomorphologists in the administration and management agencies, (ii) medium-high requirements of time and data, (iii) absence of simple automated classifications, and (iv) that the use of hydrogeomorphological variables remains optional (Newson, 2002; Blue and Brierley, 2015). It should be noted that WFD is a management tool and as such should be able to be applied by technicians without the need for specialized scientific knowledge. Although there are widely used geomorphological classifications like the Rosgen (1994, 1996) and Montgomery and Buffington (1997, 1998) classifications, as well as the River Styles Framework (Brierley and Fryirs, 2005), these generally require time, observations, and expertise for their application.

The present study aims to develop a simple geomorphological classification tool that can be applied rapidly and adjusted to fit tight budgets. We propose adopting a different level of spatial organization: geoecological units called lithotopo units or LTUs (Montgomery, 1996) that identify areas with similar topography and lithology, and thus analogous geomorphological processes. The inclusion of LTUs as an obligatory descriptor within System A would make it possible to organize river management according to geomorphological criteria. We tested this classification in the Galicia region of Spain (Fig. 1) to establish a protocol for the development of LTUs that is transparent, objective and quantitative. Finally, we evaluated the validity of basin scale identification of LTUs using channel-scale variables.

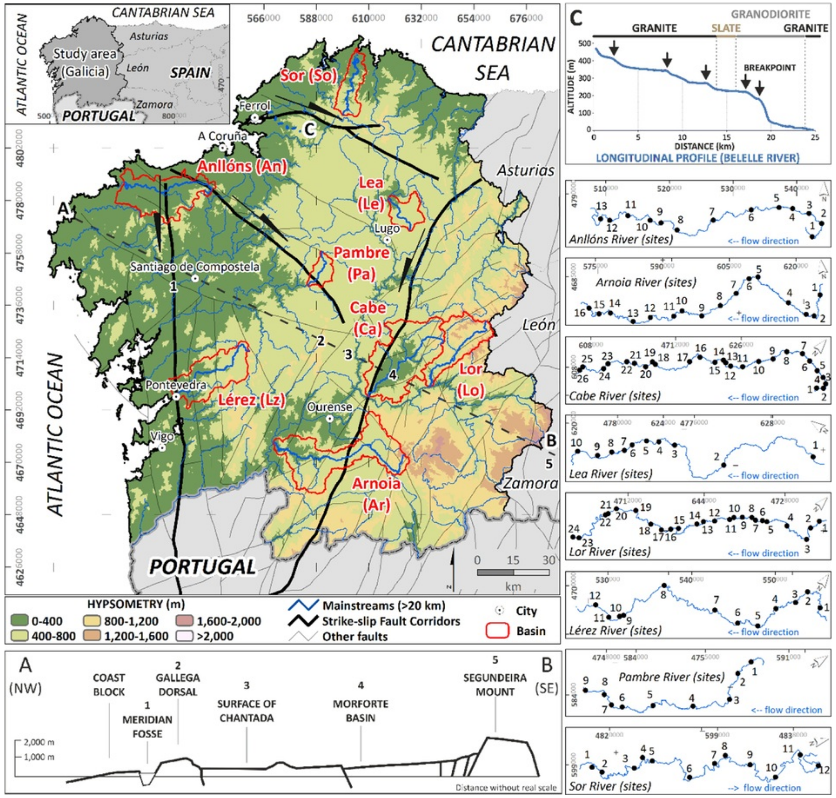


Fig. 1 Location and hypsometric characteristics of the study area. Map shows location of: (i) NW-S topographic profile illustrating relationship of physiographic expression to geological faults (lower left); (ii) example of a longitudinal profile (Belelle River) with its topographic and lithological characteristics (upper right); and (iii) maps showing distribution of numbered sites along each river used for validation.

alt-text: Fig. 1

2 M~~ETHODOLOGY~~ethodology

2.1 Study site

The study area covers a ~30,000 km^2 portion of the NW Iberian Peninsula (Fig. 1). The tests were made analyzing sample sites distributed across eight river basins (Anllóns, Arnoia, Cabe, Lea, Lor, Lérez, Pambre and Sor), which cover almost 12% of Galicia (Table 1). In these basins, dendritic drainage patterns predominate, though some areas exhibit trellis morphology.

Table 1 Features of the basins chosen for the cartographic validations. Key: sd (standard deviation), Cr (circularity ratio), Tt (travel time), Dd (drainage density), B (basic), G (granite), M (metamorphic), S (sedimentary), and C (calcareous).

alt-text: Table 1

Basin		River (km)	Altitude (m)				Slope (degree)				Area (km²)	Cr	Tt (h)	Dd(km/km²)	Lithology (%)				
ID	Name		Max	Mean	Min	sd	Max	Mean	Min	sd					B	G	M	S	C
An	Anllóns	64.6	559.0	226.8	0.0	119.4	65.1	7.2	0.0	5.8	520.5	0.3	17.6	1.0	35.9	18.0	44.4	1.7	
Ar	Arnoia	96.0	1612.0	625.4	66.0	218.9	65.7	10.4	0.0	7.9	741.4	0.2	21.1	1.2		54.3	34.9	10.8	

Ca	Cabe	59.6	1303.0	510.2	126.0	175.9	72.5	9.4	0.0	8.2	732.3	0.3	14.1	0.9		12.2	52.4	34.4	1.0
Le	Lea	23.6	853.0	481.4	389.0	72.0	50.3	26.7	0.0	4.7	154.8	0.5	7.0	0.6		21.8	44.2	32.2	1.7
Lo	Lor	57.8	1638.0	892.3	224.0	272.7	79.5	23.8	0.0	10.2	368.6	0.3	13.3	1.5			86.6	4.2	9.1
Lz	Lérez	62.7	1015.0	439.5	0.0	223.0	61.7	12.1	0.0	7.3	453.2	0.4	17.0	1.5	0.3	65.6	31.6	2.5	
Pa	Pambre	23.7	797.0	536.8	335.0	81.8	44.9	7.5	0.0	5.4	97.8	0.6	7.8	1.0	13.2	70.4	13.2	3.2	
So	Sor	61.8	806.0	409.3	0.0	147.8	65.6	15.5	0.0	9.8	201.9	0.4	18.0	1.7		4.8	94.6	0.6	
Ga	Galicia		2,122.0	502.3	0.0	305.5	78.3	10.5	0.0	8.3	~30·10³			0.9	2.8	37.4	49.4	9.9	0.4

The average precipitation in Galicia is 1~~200-1,~~200-1300 mm/year, although it varies substantially due to relief effects (Martínez-Cortizas and Pérez-Alberti, 1999). High runoff and streamflow for this portion of the Iberian Peninsula (Pérez-Alberti, 2000) reflects high levels of precipitation and perennial base flow.

Drainage basins were chosen for inclusion in the validation study based on the application of a reach diversity index (see Horacio, 2014). This index measures the diversity of reaches of a river considering (i) the abundance of different types according to a variable, and (ii) the distribution of the reaches in the space, that is to say, by their continuity or fragmentation. Calculation of the geomorphological diversity of Galician rivers was carried out over 20 km river lengths using the following geomorphological variables: incision ratio of the valley, amplitude of the valley, lithology, sinuosity of the river reach, slope of the valley, and density of faults and fractures. The assessment was conducted using a Geographic Information System and correspondence analysis. The application of that study revealed that the eight basins analy~~z~~sed are representative of the diversity of geomorphological environments in Galicia.

The geological history of the NW of the Iberian Peninsula produced a morphological expression that Hernández-Pacheco (1949) described as resembling piano keys made up of *horst and graben* terrain, with a gradual inclination from east to west (Solé, 1983). This configuration reflects trans-tensional or transpressive regimes associated with strike-slip faults (de Vicente and Vegas, 2009; de Vicente et al., 2007; de Vicente et al., 2011). The five main geomorphological features of Galicia consist of: mountain ranges, grabens or depressions, upland surfaces, faults and fractures, and the fluvial network (Pérez-Alberti, 1993). The first four are morpho-structural features (see profile A-B in Fig. 1), while the fluvial network reflects the main features of the relief (Martín-Serrano, 1991).

The Galician fluvial network is antecedent and bears a close relationship to regional tectonic development and evolution since the Cenozoic (Pérez-Alberti, 1982). From a tectonic perspective, Galicia hosts two kinds of rivers or reaches: those that follow the tectonic grain of structures (Pérez-Alberti, 1993), and those that follow the course of their tertiary ancestors and passively follow subsequent alpine tectonic modifications (Vidal-Romaní, 1996). The deep incision of the fluvial network derives from intense fragmentation of the old igneous craton on which Galicia rests (Martín-Serrano, 1991). This process gave rise to striking topographic contrasts characterized by a combination of sectors with pronounced elevation differences and others with little relief. Gorges occur in all lithologies, and sinuous rivers are apparent in both alluvial plains and plutonic massifs.

Lithologically, over 85% of the surface of Galicia rests on granitoid and metamorphic rocks (schist, gneiss and slate; Table 1). The former comprises 37% of the surface and the latter 49%. The eastern strip of Galicia is dominated by slate with quartzite bands (e.g., Lor River). In the central-western sector there is a combination of sedimentary deposits with schists and granitoid rocks (e.g., Lea River). The SW sector of Galicia is covered mostly by granitoids (e.g., Lérez River). All together, the basins selected for the validation of the LTUs (see Fig. 1) cover the lithological diversity in Galicia. The Cabe River basin, in particular, is a synthetic expression of the diversity of the lithological as well as geomorphological environments that exist in Galicia.

2.2 Conceptual framework

The LTU protocol shown in Fig. 2 is designed to be used within the limits of a geomorphological province ~~—~~– a region with similar land forms, hydrologic, erosional and tectonic processes over areas greater than 1,000 km^2 (Montgomery and Buffington, 1998). In this sense, Galicia is considered an independent geomorphological province (Pérez-Alberti, 1993). The LTUs are delimited on the same level as river basins (50–500 km^2) (Montgomery and Buffington, 1998). However, LTUs differ from river basins in that they identify sectors in which different geomorphological processes influence ecological processes (Montgomery, 1996; Brierley et al., 2006; Wheaton et al., 2011). While river basins provide a logical basis for resource management, their spatial limits do not generally coincide with the underlying lithological framework. Taking the river basin as the standard unit in the sense established by the WFD can mean that some basin reaches may have more in common inside a LTU that crosses several basins than inside several LTU forming one single basin (Fig. 2). In this study the river basin is regarded as the first level of spatial organization (Newson, 2002) internally structured according to LTUs (Montgomery, 1996; Omernik and Bailey, 1997; Brierley and Fryirs, 2005). In contrast to other classifications with a greater biological orientation (Pennak, 1971; Wright et al., 1984; Holmes, 1989;

Jowett and Duncan, 1990; Naiman, 1998; Wright et al., 1998), the hierarchical classification of Montgomery and Buffington (1998) has a clear hydrogeomorphological focus compatible with using LTUs to facilitate regional comparison of fluvial systems.

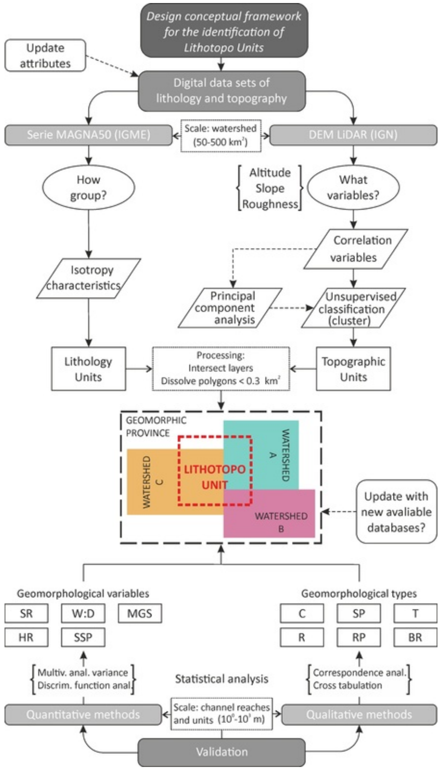


Fig. 2 Methodological workflow for the development and validation of LTUs as used in this study. Where the geomorphological variables are: Sinuosity ratio (SR), Hydraulic radius (HR), Mean width:depth ratio (W:D), Specific stream power (SSP), Median grain size (MGS). And the geomorphological types: Cascade (C), Rapid (R), Step-pool (SP), Riffle-pool (RP), Table (T), Bedrock river (BR).

alt-text: Fig. 2

The conceptual diagram in Fig. 2 represents the work protocol followed to generate (top) and validate (bottom) LTUs. The diagram identifies two working tracks. The first consists of the cartographic production of the LTU through lithological and topographical parameters. The second consists of determining quantitative geomorphological variables. Each approach proceeds on different scales (Fig. 2). The cartographic production is on a basin-scale (50–500 km^2); validation variables were assessed on a reach and channel unit scale (10^0–10^3 m). Channels reflect the combination of basin characteristics and geomorphological processes that have affected them (Amoros and Petts, 1993; Sear et al., 1994) and the use of channel unit properties for validation involves employing finer-scale data on the fluvial system with a greater relevance in hydromorphological studies (Ollero, 2007).

2.3 Cartographic methods

Cartographic analyses were produced in the geodesic reference system ETRS89 with UTM (zone 29-N) projection using ArcGIS 10.x ©ESRI and SAGA (*System for Automated Geoscientific Analyses* 2.0.8). Statistical calculations were made with R software. Additionally, WinXSPRO 3.0 was also used for calculations of hydraulic geometry and those derived from them. STREAM Module 4.0 (Spreadsheet Tools for River Evaluation, Assessment and Monitoring) was used for the sedimentological study. The hydrographic cartography employed belongs to the *Territorial Information System of Galicia* (http://mapas.xunta.es/portada) with a 1:25,000 reference scale.

2.3.1 Scale

Following the scale on which Montgomery (1996) first proposed identifying LTUs (50–500 km^2), we adopted 1:50,000 as the reference scale for the development of our LTUs. The lithological cartography employed the same scale. The topographic cartography derives from a digital elevation model (DEM) based on a 1:25,000 scale with a spatial resolution of 5 m grid-cell size. In order to integrate data from both scales the DEM has been re-gridded to 10 m grid-cell size resolution (scale 1:50,000).

The minimum geomorphological unit (MGU) mapped was fixed at 0.27 km^2 based on the following formula:

$$MGU = 300 \cdot MMU = 300 \cdot (Lpv \cdot E \cdot 3)^2 \tag{1}$$

where MMU is the minimum mapping unit (m^2) (MacEachren, 2004), Lvp is the limit of visual perception (0.2 mm in the map, that is, 0.0002 m) and E is the map scale (50,000). Integrating these values into (Eq. (1)) yields an MGU of 270,000 m^2.

Thus, the MGU for a square-shaped polygon would have a size of 520 × 520 m. A river that crosses such a unit has a minimum length of ~0.5 km, though in practice variability in the shape of the polygons can generate very small reaches. Hence, we fixed the minimum length of each river reach at 300 m. Linear elements (rivers) and polygonal elements (LTU) smaller than 300 m and 270,000 m^2, respectively, were merged in GIS with the biggest neighboring element in the case of polygons, or with the longest upstream or downstream reach in the case of linear elements.

2.3.2 Lithology

The lithological units (LU) were obtained from the lithological cartography of the Proyecto MAGNA, carried out on a 1:50,000 scale by the Geological and Mining Institute of Spain (IGME) (http://www.igme.es/). These units exhibit great homogeneity in regard to the geomorphological behavior of a river (Pike et al., 2010). The resulting lithological regionalization depends on the mechanical behavior and erosion resistance of the rock. To reflect this behavior, the study area has been classified according to those physical properties of the lithology that have to do with direction (isotropy) (~~Winter, 2009~~Winter, 2010). Other studies take into account the chemical composition of the rocks for their lithological classifications (Vidal-Abarca et al., 1990; Weiß et al., 200~~8~~7; Pike et al., 2010). We give particular importance to the anisotropy of the rock.

For the cartographic development of the LU, it was necessary to merge and refine the eighty-eight 1:50,000 map sheets that cover the territory of Galicia. Some contacts between map sheets give rise to sudden changes in lithological types, as the study and mapping criteria of the IGME were not homogeneous across all map sheets (Castelao-Gegunde et al., 1985). Such problems were dealt with manually to obtain an overall synthesis.

2.3.3 Topography

The basic topographical information was derived from a DEM with a spatial resolution of 5 m and in ASCII format obtained from the National Geographic Institute (http://www.ign.es/ign/main/index.do). A dual approach was necessary to develop homogeneous topographical units (TU) representative of a type of relief (Weibel and Heller, 1991; Felicísimo, 1994) based on what variables are employed to define the relief and how they are grouped (Fig. 2). As representative relief variables we selected altitude, slope, and roughness (Weibel and Heller, 1991; Barredo and Bosque-Sendra, 1996; Villota, 1997; Wasson et al., 2002; Olaya, 2004; Pike et al., 2008). All three variables originate in the DEM but each carries different information (Felicísimo, 1994; Márquez, 2004; Evans, 2012). The grouping of variables was done in a cluster unsupervised classification analysis (Mayer et al., 2014).

The altitudinal value was taken directly from the DEM. At a given point on a surface z f(x, y), and the slope (S) was defined as a function of the gradients in x and y (Burrough and McDonnell, 1998):

$$S = arctan\sqrt{f_x^2 + f_y^2} \tag{2}$$

With respect to the roughness parameter, there is no consensus as to its definition and calculation (c.f., Zevenbergen and Thorne, 1987~~,~~; Jenness, 2004; Sappington et al., 2007), but it can be defined as a measure of the irregularity of the terrain, that is, as its heterogeneity (Pike et al., 2008). We calculate the roughness of the terrain according to the proposal of Riley et al. (1999):

$$TRI_{rc} = \sqrt{\sum_{i=r-1}^{r+1} \cdot \sum_{j=c-1}^{c+1} \cdot \left(e_{i,j} - e_{r,c}\right)^2} \tag{3}$$

where TRI is the Topographic Ruggedness Index, e is the altitude of the pixel corresponding to row r and column c. As far as the roughness is concerned, there is no difference in being at the top or at the bottom of the valley; what matters is the slope of the nearest environment (Goerlich and Cantarino, 2010). This point is crucial to characterizing the topographical characteristics of the relief of Galicia (Pérez-Alberti, 1993).

2.4 Model validation

Validation should serve to establish whether reaches that cross an LTU have a different geomorphological behavior from reaches that cross another LTU (Thompson et al., 2008; Horacio, 2012). The validation model follows both a quantitative and a qualitative procedure. For the first case, five geomorphological variables were selected on the reach and unit scales (Table 2). All of them are commonly used in studies of fluvial geomorphology (Knighton, 1998; Newson et al., 1998a; Lawlor, 2004; Petit et al., 2005; Lord et al., 2009; Latapie, 2011; Bizzi and Lerner, 2015; Jaeger, 2015). Planform sinuosity (SR) and channel cross-section attributes (hydraulic radius, HR, and width to depth ratio, W:D) are important geomorphological descriptors of channel type at the reach scale. Channel substrate (MGS) is an important component of fluvial habitats at the mesohabitat scale. Specific stream power (SSP) is a driver of geomorphological processes that affects channel substrate, planform and cross-section. Measurements were done in 122 sites divided across the 8 validation rivers (see Fig. 1): 26 on River Cabe, 24 on Lor River, 16 on Arnoia River, 13 on Anllóns River, 12 on Lérez River, 12 on Sor River, 10 on Lea River, and 9 on Pambre River. Supplementary data 1 shows the data of all five variables for the 122 sites.

Table 2 Validation variables.

alt-text: Table 2

ID	Name	Channel scale		Measure	Reference
		Reach	Unit		
SR	Sinuosity ratio	x		form	Brice (1964)
HR	Hydraulic radius		X	dimension	Leopold and Maddock (1953)
W:D	Mean width:depth ratio		X	shape	Leopold and Maddock (1953)
SSP	Specific stream power		X	energy	~~Bagnold (1960),~~Bagnold (1960) and Bull (1979)
MGS	Median grain size	X	X	solid discharge	~~Wolman (1953)~~Wolman (1954)

The channel-forming or bankfull discharge marks the most influential level of reference in the geomorphology of a basin (Charlton, 2008). This discharge, which is linked to the river's hydraulic geometry and sediment transport (Leopold and Maddock, 1953), generally serves as the discharge of reference for the calculation of variables on the basin scale (Table 2). From an ecological point of view, the channel-forming discharge has more relevance than the average discharge on which the discharge-area relationship is based (Miller et al., 2010; Rice et al., 2010b). Calculation of the bankfull discharge followed the SNCZI geomorphological procedure (SNCZI, 2011). The percentage of rock at each site also was quantified, distinguishing bedrock rivers from alluvial rivers when the percentage of rock exceeded 80% of the cross-section, a distinction based on data in Montgomery and Buffington (1997) and Tinkler and Wohl (1998).

The calculation of the sinuosity ratio was done along a reach length ten times the local channel width (Copeland et al., 2000). The specific stream power, SSP (W m^{-2}), was obtained by means of the following formula (Bagnold, 1960, 1966):

$$SSP = \frac{\rho \cdot g \cdot Q \cdot S}{w} \tag{4}$$

where Q is the bankfull discharge (m^3 s^{-1}), S is the slope of the water surface, g is the gravitational acceleration (9.8 m s^{-2}), ρ is the volumetric water mass (1,000 kg m^{-3}), and w is the channel width (m).

The qualitative procedure of the validation model relates our results to other widely used fluvial classifications. Thus, during fieldwork we classified each site into six geomorphological types (GT, hereinafter) resulting from combining the classifications of Montgomery and Buffington (1997), Newson et al. (1998b) and Payne et al. (2004).

The six GTs were developed on the channel segment and reach scales, and are divided into two levels: bedrock rivers (BR) and alluvial rivers (cascade, C; rapid, R; step-pool, SP; riffle-pool, RP; and table, T). Supplementary data 1 shows the GTs to which each site belongs according to this classification. Since the GTs of cascade, step-pool and riffle-pool are well-known within the scientific community, their characteristics do not require further explanation (Montgomery and Buffington, 1997). The GT rapid is associated with broken standing waves (Newson et al., 1998b). The category table is taken from works on ecology and biology (Payne et al., 2004). It is found in sectors with a low or very low slope, and with gravel and sand granulometries, though some pebbles can also be found. The designation of each GT was made by observations in the field, and supporting topographic and sedimentological data (e.g., slope and median grain size).

To test quantitatively whether the LTUs identified above have "geomorphological coherence" we applied multivariate analysis of variance (Kruskal-Wallis test) to see if there were significant differences between the five control variables and LTUs types. In addition, a discriminant function analysis was used to calculate which variables better differentiate the types of LTUs and how many variables are necessary to reach the best classification. In addition, correlation test and descriptive statistics analysis were used. For the qualitative method, the data were analysed using correspondence analysis in order to evaluate the degree of association between LTUs and other fluvial classifications; as well as a cross tabulation and chi squared test to analyse the link among LTUs and GTs categories.

3 R~~ESULTS~~esults

3.1 Cartographic development of the LTUs

The map of LTUs results from the assemblage of the Lithologic Unit (LU) and Topographic Unit (TU) cartography, such that the union of LUs and TUs defines the LithoTopographic Units (LTU) (Fig. 3). The lithological cartography for Galicia was organized into three categories: isotropic rocks I (crystalline, compact and consolidated materials), isotropic rocks II (loose or little consolidated materials), and anisotropic rocks (compact materials that exhibit marked orientation or foliation). The first category includes granitoids, alkalines, calc-alkaline granitoids, amphiboles, gabbro; the second includes tertiary deposits and quaternary deposits; the third includes gneiss, slate, quartzite, limestone, peridotite, serpentinite, eclogite, granulite and schists.

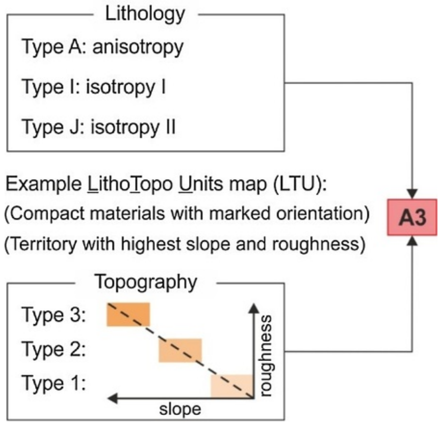


Fig. 3 Example of flowchart to make the Lithotopo Units.

alt-text: Fig. 3

The cartography of the topographic units (TU) was done with GIS and supported by map algebra. Cluster techniques of unsupervised classification require easily distinguishable classes (Barredo and Bosque-Sendra, 1996). The degree of separability among variables was determined by means of Spearman's non-parametric test. For the whole of Galicia, the correlation coefficient for variables is high and positive between slope and roughness (0.94), and low and positive between altitude and slope (0.24) and between altitude and roughness (0.26). When individually applied to each basin, the Spearman's tests produce similar results. The low correlation of the altitude variable is due to the arrangement of the erosion surfaces at different altitudinal levels (see Figs. 1 and 4), and we thus ruled out using this variable in the development of the LTUs. For Galicia, altitude is a more characterizing factor from a biological rather than geomorphological perspective (Rodríguez-Guitián and Ramil, 2007), due to the small altitudinal range (Pérez-Alberti, 1982) and of the structural arrangement of the relief as a series of tiers (Nonn, 1966) (Fig. 4).

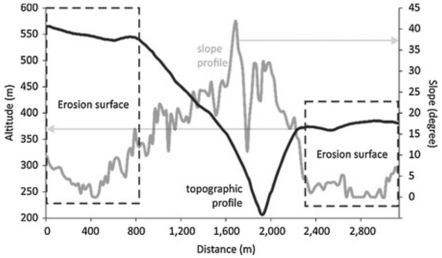


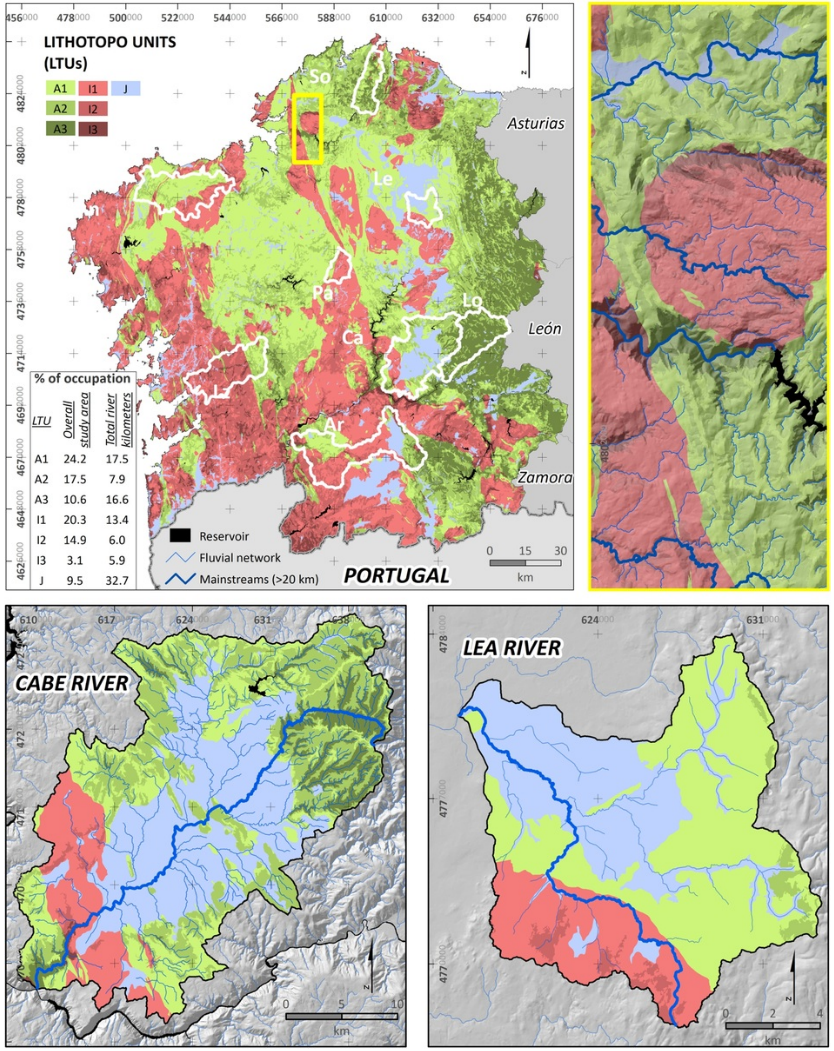
Fig. 4 Example of cross-sectional profile displaying erosion surfaces. Cabe River (x,y cross-section: 612891, 4702373).

alt-text: Fig. 4

The close correlation between the variables of slope and roughness made it necessary to conduct a principal component analysis in order to ensure the use of independent variables in the cluster statistics (Fig. 2). The first slope-roughness component contains more than 90% of the variance. The number of clusters (topographic units, TU) was set at three. We justify this choice based on the facts that: (i) the zoning of the study area is balanced by a number of units that reflect the variability of environments (Pérez-Alberti, 1993); and (ii) the study area is not excessively fragmented. This gives the river room to adapt geomorphologically to the topographic environments across which it runs (Wohl and Merritt, 2008).

The three TUs established reflect specific relief characteristics. Each TU falls within specific ranges of altitude, slope and roughness, with a gradual increase from TU 1 to TU 3. The average values of altitude (m), slope (degree) and roughness (m) of each TU are, respectively: 395, 1.8, 3.1 (TU 1); 503, 6.4, 5.6 (TU 2); 706, 14.1, 8.3 (TU 3).

A GIS-based overlay between the lithological map and the topographic map produced a new layer that represents the LTUs. We then merged polygons smaller than 270,000 m^2 (the minimum geomorphology unit). The combination of layers results in 9 LTU types designated by a letter that indicates the type of prevailing lithology (A, anisotropic; I, isotropic I; J, isotropic II), followed by a number that indicates the type of relief unit (TU 1, TU 2, TU 3) (Fig. 5). For example, the LTU A3 = compact materials with marked orientation (LU A) + territory with highest slope and roughness (TU 3). Fig. 5 shows the percentage (%) of occupation of (i) each type of LTU in the overall study area, and (ii) the lithotopographic types in terms of total river kilometers, after combining the LTUs with the rivers with a length of over 20 km. Because of their low percentage of spatial occupation (<1%), LTUs J2 and J3 were merged with LTU J1, which is renamed LTU J. This results in a total of 7 LTUs.



% of occupation

LTU	Overall study area	Total river kilometers
A1	24.2	17.5
A2	17.5	7.9
A3	10.6	16.6
I1	20.3	13.4
I2	14.9	6.0
I3	3.1	5.9
J	9.5	32.7

Fig. 5 Lithotopographic units (LTUs) in the study area, focusing on three examples of a sector of the NW of Galician and the basins of the Cabe and Lea Rivers. The figure includes the percentage (%) of occupation of each type of LTU in the overall study area and of lithotopographic types in terms of total river kilometers.

alt-text: Fig. 5

3.2 Validation

In the first quantitative validation analysis, the Kruskal-Wallis nonparametric test was applied (the variables did not meet normality and homogeneity) to see if there were significant differences between the control variables and the LTUs types. As a null hypothesis (H_0) it was considered that there are no significant differences among LTUs types, and as an alternative hypothesis (H_1) there are significant differences among LTU types. The test shows a significant differences between the types of LTUs according to SSP and MGS (significance <0.05). The SR, HR and W:D variables have significance values higher than 0.05 (0.614, 0.496, 0.542, respectively), indicating that the LTUs do not differentiate these variables.

In the second quantitative validation analysis, we applied a discriminant analysis to determine which variables have the most power in allocating sites to different LTUs (Fig. 6). The process was carried out according to two scenarios: (i) including all the sites, and (ii) excluding the bedrock rivers from the calculation (see Supplementary data 1). The characteristics of the validation variables in bedrock rivers are so diverse that they form a GT of their own (Tinkler and Wohl, 1998; Ortega and Durán, 2010). To this variability we must add the difficulty in evaluating their hydraulic geometry at channel-forming discharges (Modrick and Georgakakos, 2014). Bedrock rivers make up 6.6% of the sites. In both scenarios the variables SSP and MGS are the ones that have the greatest explanatory power for the validation of LTUs types (Fig. 6). The information of the other variables is secondary. MGS is closely related to factor F1 in both scenarios. SSP divides its discriminating power between the factorial axis F1 and F2 (Fig. 6).

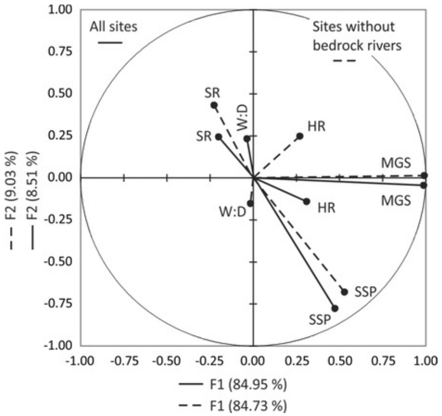


Fig. 6 Factorial graph of the discriminant function analysis applied to the testing variables. Key: MGS (median grain size), SSP (specific stream power), HR (hydraulic radius), SR (sinuosity ratio), W:D (width-depth ratio).

alt-text: Fig. 6

Fig. 7 shows the behavior of each LTU according to the two variables with the greatest discriminating power (SSP, MGS). We employed these variables to individualize the types of LTUs. The calculations were done without the outlier data of each variable. These represent 7.0% (SSP) and 8.8% (MGS) of the sites. The lowest SSP and MGS values correspond to TU (topographic unit) number one, and the highest to TU number three. Each TU exhibits different characteristics, defined by the type of LU (lithologic unit) to which it belongs. The medians of the SSP of TU 1 of TU 2 are below 120 W m^{-2} and 240 W m^{-2}, respectively. TU 3 exceeds 340 W m^{-2}.

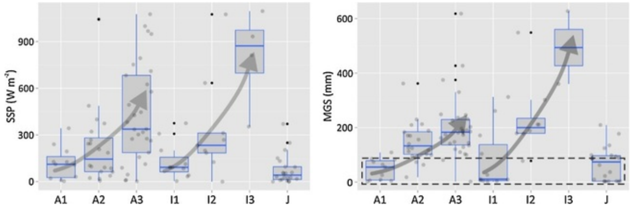


Fig. 7 Representation of the LTUs (lithotopographic units) according to the variables SSP (specific stream power) and MGS (median grain size).

alt-text: Fig. 7

The characterization of LTUs according to MGS also shows differences between LTUs, LUs and TUs (Fig. 7). There is an increase in sediment size between TU 1 and TU 3 of LU A and LU I. This growth is more progressive and less accentuated among the LTUs of LU A. The range of LTUs of LU A is lower than that of LTUs of LU I. Even the median of LTU I2 is slightly higher than that of LTU A3. The LTU J has lower values of SSP and MGS, however, for the variable MGS the median value of LTU J is higher than that of LTU A1 and I1 (Fig. 7).

Supplementary data 2 shows the qualitative cross tabulation and analysis of correspondences between LTUs and the GTs cascade, rapid, step-pool, riffle-pool and Table Supplementary data 2 (A and B) also shows the results of cross tabulation between LTUs and GTs. A Chi-squared test yields a significance level <0.05, so the hypothesis that LTUs and GTs are associated is not accepted. However, cross-tabulation analysis yields additional interesting data for the study. The average percentage of the maximum frequency of a LTU with a GT is ~60%, with LTUs A1 and J being the most associated with a GT (RP) (75% and 76% respectively), and I3 and A3 (44% with GT-C and 46% with GT-RP, respectively). The results of the analysis of LU and TU follow this trend (Supplementary data 2-A). Considering the second maximum association value between LTUs and GTs (i.e., the two maximum association values), all frequencies are higher than 80% (minimum I3 with 67% and maximum J with 100%).

60% of the GTs are riffle-pool (RP), followed by rapids (R) with 16% of the sites, and finally with a presence of less than 10% are the rest of GTs. The riffle-pool (RP) types are present in all the LTUs (26% J and 3% I3, mark the extreme values), which influences notably the results of chi-squared test. Other GTs, however, are clearly related to a particular LTU: bedrock (BR) and step-pool) SP by 75% with A3 and table (T) by 60% with LTU J. The cascade (C) and rapid (R) GTs do not have such clear dominance in a particular LTU, but its presence is more diversified in LTUs. Considering the LU and TU frequencies are more concentrated in one type. Thus, for example: (a) 100% of the step-pool (SP) GT occurs in LU A; (b) GT-T in LT 1; (c) bedrock (BR) and rapid (R) GTs have a frequency of ~75% in LU A; (d) and bedrock (BR), cascade (C) and step-pool (SP) GTs account for ≥75% of TU 3.

Supplementary data 2-C shows an analysis of simple correspondences with the bedrock GT excluded from the calculation. Dimension 1 neatly distinguishes the five GT. The riffle-pool (RP) type is more closely related to LTUs I1, A2, A1 and J than with the others. The respective stream power (SSP) and channel substrate (MGS) medians of these LTUs are 125 W m^{-2} and 110 mm (Supplementary data 2-C). The cascade (C) type is closely linked to LTU I3, while rapid (R) and step-pool (SP) types are linked to A3-I2 and A3-A2, respectively. These three types have the highest thresholds of SSP and MGS. The high values of the type C are striking, with a SSP of over 2000 W m^{-2}. LTU J and A1 are associated with the lowest values of SSP (5 W m^{-2}) and MGS (55 mm).

4 D~~ISCUSSION~~iscussion

4.1 Strengths

The proposed method is dynamic (data can be updated) and open to the addition of new cartographic variables that characterize the work area. In the study carried out in Galicia, the variables of lithology, slope and roughness proved sufficient to characterize areas with the same geomorphological behavior. Altitude was excluded as an attribute when delimiting the LTUs, though we consider it of interest for classification purposes because it is useful from a biogeographical perspective. Moreover, the fact that LTUs are calculated using GIS makes it possible to cover large areas of territory at minimal cost, and to link the characteristics of a classification made at reach and channel level (with a higher economic cost) to a less detailed one (with a lower economic cost).

The importance of geomorphology for the ecological understanding of a river (Kondolf, 1995; Clarke et al., 2003; Reinhardt et al., 2010; Rice et al., 2010a,b; Wheaton et al., 2011; Bizzi and Lerner, 2012) justifies the addition of a descriptor (LTU) that organizes territory according to geomorphological criteria within the characterization rules of the WFD. In recent years there have been a number of works of ecological state evaluations that incorporate geomorphology (Elosegi et al., 2010; Wy~~ż~~zga and Zawiejska, 2012; Speed et al., 2016).

WFD recommends using river classification to achieve its ecological goals, employing different variables and features hierarchically organized from a smaller to a bigger scale (ecoregion ~~— watershed — [LTU] — fluvial segment — fluvial habitat —~~– watershed – [LTU] – fluvial segment – fluvial habitat – biological community). The drainage basin is thus characterized by its size and internally by the LTUs. With the suggested hierarchical scheme, the lithological variable is incorporated into the LTU and removed as an independent descriptive variable.

In addition, size and LTUs descriptors are complementary. The characterization proposed by the WFD on a basin scale does not necessarily provide adequate context for identifying fluvial reaches with similar ecological conditions where associated biotic characteristics can be distinguished. On the contrary, dividing a basin into LTUs means dividing it into areas with similar geomorphological behavior. These areas are thereby more closely linked to specific habitat types (Montgomery, 1999; Ibisate et al., 2011; Bizzi and Lerner, 2012; Horacio, 2015; Kondolf et al., 2016).

For example, identifying LTUs helps to show why the increase in stream power (SSP) in the Cabe River is not proportional to the drainage basin size (Fig. 8). Four sectors along on the Cabe River that illustrate the development and validation of the LTUs show the utility. Each sector represents a GT (R, RP, T and C) linked with a specific LTU (A3, A2, J and I3, respectively). It can also be seen that for a short ~6 km reach (gneiss sector), the LTUs separate river reaches with different geomorphological characteristics.

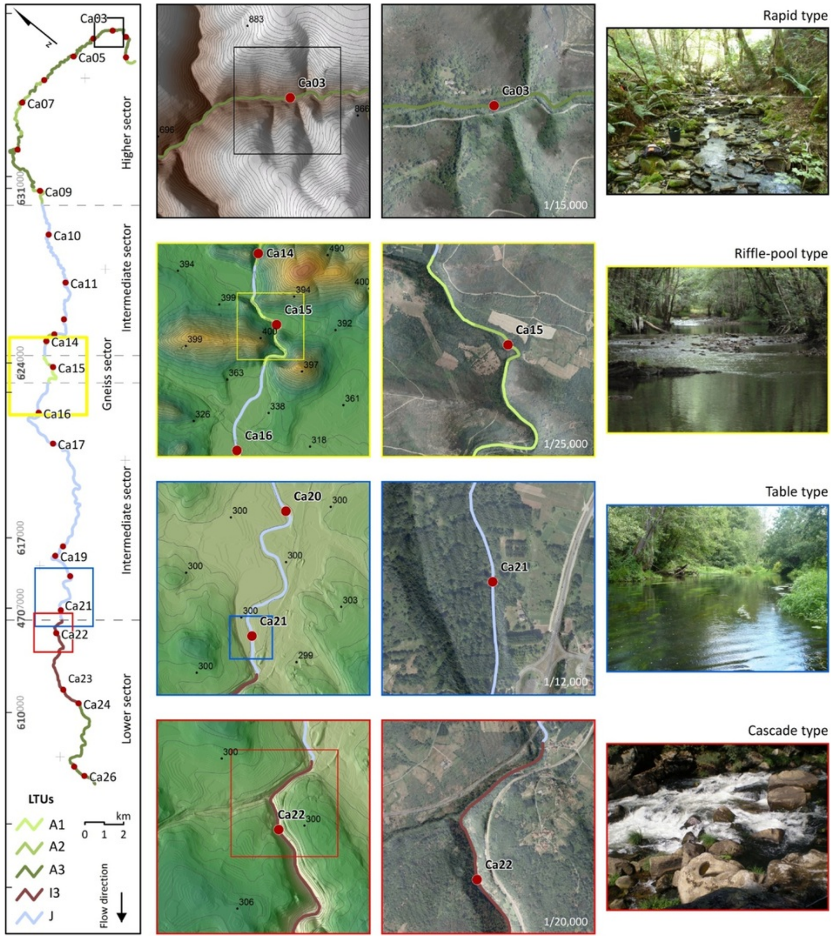


Fig. 8 Addition of the LTUs (lithotopographic units) to the WFD (Water Framework Directive) and characterization of the Cabe River according to SSP (specific stream power), MGS (median grain size), LTUs and GTs (geomorphic types).

alt-text: Fig. 8

4.2 Limitations

The conceptual framework that we propose here for the development and validation of the LTU descriptor combines principally objective criteria, but also other criteria with some subjectivity. The statistical techniques that we employed have been widely tested in the fields of hydrology and geomorphology (e.g., CEDEX, 2004~~,~~; Magilligan and Nislow, 2005; Shrestha et al., 2008; Dong et al., 2009; Leviandier et al., 2012; Piégay and Vaudor, 2016). The validation variables, as justified in the methodology section, are commonly used in studies of fluvial geomorphology. However, the five attributes selected to validate the typology are not independent. One of them influences the others and so introduces duplication in the validation process. Geomorphological processes and their associated forms determine the structure of a river system (Brierley et al., 2005; Tadaki et al., 2014), although it is difficult to separate cause and effect (Church and Ferguson, 2015). The structural factors of Galicia (lithology and tectonics), combined with other local factors, mean that the correlation between the five variables is less than 0.60 (maximum correlation between SSP and MGS: 0.56). This low correlation suggests that the geomorphological characteristics measured by each variable are relatively independent.

Fig. 7 shows that the features of stream power (SSP) and channel substrate (MGS) are closely connected with a specific LTU type. During this process of validation it is necessary to take several things into account. (i) LU I has fewer sites than LU A, which means that each site in LU I has more weight in the configuration of its boxplot. (ii) The SSP conditions of some sites do not necessarily have to be indicative of the current energy conditions that the LTU encompasses. The latter situation occurs in relict sectors where the morphology does not necessarily reflect the current characteristics of the channel. Fig. 2 suggests the possibility of updating the LTUs with new data as it becomes available, such as the more precise geomorphological cartography under development in Spain. (iii) The scale on which LTUs have been produced means that the specific characteristics of some sites are impossible to detect. For example, site An10 has greater SSP than the type of LTU to which it belongs would predict (see Supplementary data 1). This is likely caused by the greater detail of the scale used for validation. The bedrock river sites are not recognized by the LTUs because it is a fluvial style so diverse that they form a GT of their own (Tinkler and Wohl, 1998; Ortega and Durán, 2010).

The MGU (minimum geomorphology unit) has been arbitrarily designated but verified by the validation process. The categories that make up the LUs have been regrouped according to characteristics coherent lithologically. The initial number of groups of TUs should be low, as far as possible, but it is the responsibility of the analyst to accept the final topographic organization of the territory for the cluster unsupervised classification analysis. For this, good geomorphological knowledge of the study area is essential.

5 C~~ONCLUSIONS~~onclusions

In summary, this paper shows the power of LTUs as a flexible tool for the classification of rivers. Our method contributes to advancing the geomorphological analysis of river systems and understanding of large areas. Our framework is based on GIS procedures with wide applicability in other areas, and it is amenable to enhancing and updating with new variables.

The LTUs are not an alternative to the WFD typology; they are a complement that, we believe, improves it. LTUs are a tool aimed at helping to meet the WFD objectives in the 5~~-~~-year extension granted to Member States since 2015. The development and interpretation of LTUs requires hydrological and geomorphological knowledge and are only applicable to scale of basin, so that uses at different scales may mean that the expected results are not achieved.

Looking to the future, two new lines of research are planned based on this study: (i) applying the protocol to new territories, and (ii) increasing the number of validation sites to strengthen the characteristics that best define LTUs. In addition, the future availability of highly accurate lithologic and geomorphological cartographies will also assist in the improvement of LTUs.

Uncited references

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2017.08.043~~), Weiß et al. (2007), Winter (2010), Wolman (1954) and Wyzga and Zawiejska (2012)~~.

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Appendix A. Supplementary data

The following are Supplementary data to this article:

Multimedia Component 1

Multimedia Component 2

Queries and Answers

Query: Please check the dochead for correctness.
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Query: Please provide the volume number, issue number and page range for the bibliography in Refs. Hawkins and Norris, 2000; Wohl et al., 2005.
Answer: We have deleted the Ref. Hawkins and Norris (Q7). Respecto to Wohl: WATER RESOURCES RESEARCH, VOL. 41, W10301, doi:10.1029/2005WR003985, 2005

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Answer: The correct year is 2008. You can look this clicking here: https://link.springer.com/article/10.1007/s10750-007-9247-2. Please, can you modify the Ref. in the text? Thanks.

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