Morpho-fluvial analysis of headwater catchments – An example from the Central-Eastern Pyrenees.

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Abstract

Geomorphometry of headwater catchments has been poorly reported in the Central-Eastern Pyrenees. This study presents a series of parameters obtained for Central-Eastern Pyrenean headwater catchments. The database consists of 3005 1st- and 655 2nd-order catchments. These catchments have been digitalised, identified, and attributed a value for each parameter. The parameters investigated are divided into three groups: relative to catchments, relative to streams and morpho-hydrological ratios. Histograms reveal similarities between orders for some parameters such as mean slope or orientation, while stream orders seem to condition metrical parameters (area, perimeter, stream length). Streams have been fragmented to assess different values for slope. Values for slope over a small portion of the stream near the outlet seem to show clearer differences between orders. With regard to morpho-hydrological ratios, catchments show better distinctions between orders for the Melton and Lemniscate ratios than for the form factor or the basin elongation. The power-law relationship between catchment area and stream length recognised for large fluvial systems is shown here to follow a linear trend at small values. An attempt to identify the morpho-structural regionalisation differentiating the Axial Pyrenees from the pre-Pyrenees is made based on the parameters. However, applying the methodology to other environments could improve the context of the current results. Similar studies could also benefit from the development of such databases.

Keywords: GIS / Pyrenees / headwaters / catchments / digital terrain data

1. Introduction

This article is an investigation into the geomorphology of catchments, and more specifically the geomorphometrics of headwater catchments. This broad theme has long received attention from geoscientists (Strahler 1957; Melton 1965; White et al 1996; Lin and Ogushi 2006; Perucca and Angilieri 2011; De Paola et al. 2013).

Geographical information systems (GIS) have greatly contributed to the advancement of geomorphology. GIS is widely used in the reconstruction of landscapes. The scope of application is vast and includes, but is not limited to, such broad themes as tectonics (Jordan et al. 2005; Font et al. 2010) and glacial geomorphology (Napieralski et al. 2007), as well as more narrow themes such as debris-flow fans morphometry (Welsh and Davies 2011). However, geomorphological features are often the main focus of such studies (e.g. Stager et al. 2010) and studies on soils (Rezapour 2014), karsts (Huang et al. 2014), caves (Duc and Guinea 2014), and beaches (Merlotto et al. 2014) have benefitted from morphometry. Streams and catchments have similarly been the focus of past studies (Youssef et al. 2011; De Paola et al. 2013; Magliulo et al. 2014).

The parameters used in morphometric studies depend on the study area and study objectives. Literature provides numerous examples of the parameterization of catchments and streams in GIS environments (Obi Reddy et al. 2004; Ng 2006; Ehsani and Quiel 2008; Kar et al. 2009; Youssef et al. 2011). The parameters used in this article reflect the fluvial and morphometric aspects of the information sought and the database presented herein is the backbone of statistical debris-flow susceptibility models (Chevalier et al. 2013). For this reason the list of parameters includes information on topography, orientation, slope, and stream order.

Past morpho-fluvial studies have focused on Spanish landscapes (Cammeraat 2002; Bathurst et al. 2007; Lana-Renault and Regües 2009; Troiani et al. 2014). White et al. (1996) studied sediment transport rates in a small high-mountain catchment in the central Pyrenees and further studies performed at catchment-scale are numerous (Seeger et al. 2004; Garcia-Ruiz et al. 2005; Ng 2006; Kiel et al. 2010, Troiani et al. 2014). Larger-scaled studies are small in number though, probably due to their likely complexity (Cammeraat 2002; Dragut et al. 2011). However, outside Spain, Bhagwat et al. (2011) investigated spatial variations through the characterization of 5th-order catchments, Kompani-Zare et al. (2011) identified 146 1st-order catchments in Iran and investigated 9 morphometric factors, Gibbs et al. (2010) reported morphometric results for 4 Australian catchments, and Erkeling et al. (2010) looked at the morphometry of dendritic valleys on Mars.

This article is a study of headwater catchments that have experienced historic glacial and tectonic activity, and where recent erosional processes are often reported and studied (Portilla et al. 2010; Abancó and Hürlimann 2014). Numerous mass movements and dramatic fluvial activity occur in headwater catchments and probably dictate their morphometric development. This study is a snapshot of the current understanding of the morphometrics of headwater catchments and formed the basis for debris-flow susceptibility models.

2. Study area

2.1. General settings

The Pyrenean mountain range represents the natural boundary between France and Spain and enclaves the Principality of Andorra. On shore, it is a 430 kilometres (km) range, developed following an East-West axis. The study area presented herein belongs to the Central-Eastern Pyrenees.

The range is divided in two sectors: the Axial Pyrenees and the pre-Pyrenees. ECORS Pyrenees Team (1988) comprehensively described both (Fig. 1 A). The uplift creating the Pyrenees some 40 million years ago involved material of much older age (Muñoz 1992; Teixell 1998; ICC 2003). Running from Ordovician to Devonian and including Tardy-Hercynian intrusions, the stratigraphy exhibits a dense and complex network of faults. However dense and complex, Pyrenean faults network is reported as showing little activity when compared to other exhumation rates (Fitzgerald et al. 1999; Lynn 2005).

The relief of the field site ranges from sea level to over 3400 meters above sea level (m a.s.l.). U-shaped valleys and cirques are common remnants of past glaciation, pledging for the extent and power of erosion of glaciers in the region. As a matter of fact, tills and bedrocks are the most common outcrops in the Axial Pyrenees. Deglaciation resulted in destabilizing the steep slopes developed during the Last Glacial cycle, giving rise to landslide activity. A discontinuous sequence of deposition is witnessed due to the presence of colluviums straddling over the mentioned units.

The geographical position of the Pyrenees between the Mediterranean Sea and the Atlantic Ocean, as well as between continental and oceanic huge extensions, explains its complex meteorology. Moreover, its latitudinal situation inside a temperate climate zone leads to seasonal extreme variations (Cuadrat and Pita 1997; Martin and Olcina 2001): The summer season is dry and the rest of the year is moderately humid, the highest precipitation being in autumn. A high relief combined with prevailing winds yields to weather contrasts as observed in the average annual rainfall. Precipitation ranges from 850 to 1200 millimetres per year.

2.2. Watersheds

In this contribution, a watershed is understood as an ensemble of catchments. The south-facing part of the Pyrenees has been divided in 8 units following the pre-existing, common regional extents of 8 watersheds. They cover the equivalent of the Catalan Pyrenees including Andorra (Fig. 1 B): Fluvia (Flu) / Garona (Gar) / Llobregat (Llo) / Noguera Pallaresa (NP) / Noguera Ribagorçana (NR) / Segre (Seg) / Ter / Valira (Val).

Table 1 shows, for the 8 watersheds, mean values of total area, number of catchments, and mean area and mean elevation per catchment. Values for 1st-order and 2nd-order catchments are reported.

The 8 watersheds together cover an area of 11233 square kilometres (km^2). In each watershed, 1st-order and 2nd-order catchments have been defined and serve as a base for the extraction of parameters. Catchments (and streams) have historically been characterized in terms of orders. Two systems co-exist: the one from Strahler (1952) and the other one from Horton (1945). In this article, the classification used for the subdivision of the catchments is the one from Strahler (1952) and is motivated by the wide use of this classification in hydrology and the easiness to obtain such information in GIS.

Garona and Valira are clearly high-mountain watersheds with the highest elevations generally attributed to the Axial Pyrenees. However Fluvia and Ter, which have the lowest mean elevations, majorly fall in the Axial Pyrenees too, although closer to maritime influences. Llobregat, Segre, Noguera Pallaresa and Noguera Ribagorçana spread over both Axial and pre-Pyrenees.

3. Methods

A 5m*5m digital elevation model (DEM) loaded in a GIS (ESRI 2008) was used to recreate the landscape. This digital landscape, previously divided into watersheds, was then discretized into catchments of 1st- and 2nd-order following Strahler (1952). Arc Hydro tool and GEO-HMS tool for ArcGIS 9.3 were used to recreate the drainage system of the study area. Youssef et al. (2011) used a similar method of GIS based morphometry when recreating an Egyptian drainage system to determine the risk of flash flooding. The analysis was carried out using the D8 approach (O'Callaghan and Mark 1984). Definition of streams needs a minimum drainage area for initiating the stream, which was set at 1 km^2; for this reason, no catchment has a drainage area smaller than this value. Although not capable of modelling the divergence of flow in ridge areas, it accurately captures the basin area. The flow accumulation was performed using the Jenson and Domingue (1988) algorithm and the slope's calculation follows the Burrough and McDonell (1998) approach. Other GIS tools were used, including geo-algorithms developed and adapted to this particular study.

Once the study unit (catchment) was processed and defined, the necessary information was created and assigned to each catchment. A series of parameters (Table 2) was devised, and a way to access this information was determined. It was necessary to create slope, stream order, and orientation rasters (it should be noted that the same was done with the DEM for the topographic information regarding each cell). The spatial analyst command was used. However, the use of the “zonal statistic tool” was not possible because of the overlapping of catchments. Certain catchments overlap others due to the way in which catchments are defined: 2nd-order catchments contain at least one 1st-order catchment, and so on. Instead of assessing each catchment individually, the tool would have processed only the combined information of the first two 1st-order catchments. The original code of the “zonal statistic tool” was therefore modified to allow for the processing of individual overlapping catchments. The “zonal geometry tool” was also used in this study, and its original code sufficed.

The area of each catchment was calculated, taking into account the number of cells constituting the catchment and their size (5m*5m), as well as the perimeter. Maximum, minimum and mean elevations for each catchment were defined based on the topographical data from the DEM. The mean slope of the catchment was calculated by averaging the slope value for each pixel of the catchment’s polygon. The same logic was applied to the mean orientation of the catchments. Furthermore, a best-fit ellipsoid was calculated for the area of each catchment, which was useful in calculating morpho-hydrological ratios (Table 2).

The streams within each catchment were also studied. The length for each segment of stream contained within a catchment was calculated, the origin of the steam being the point at which drainage area has reached 1 km^2. In addition, the *average slope* of each stream was calculated by dividing the sum of the slope of each pixel constituting the entire stream, from the head to the intersection, by the number of pixels. Two other slopes were also gathered. The *200 meter slope* follows the same idea as the average slope, except that it was calculated over 200 meters starting from the intersection of the catchment and going upstream. Beside, the *outlet slope* considers the slope of the stream’s segment running for 50 meters from the intersection and going upstream.

The catchments were also characterized in terms of several morpho-hydrological ratios (Zavoiana 1978; Davoren 1982). The Melton ratio (or Ruggedness number - Melton 1965), the form factor (Horton 1932), the lemniscate ratio (Chorley 1957) and the basin elongation (Schumm 1956) are reported in Table 2. The Melton ratio is an index of the average slope of a catchment and is expressed as the difference in elevation divided by the square root of the area. The lemniscate Ratio is a measure of how closely the shape of a catchment approaches a lemniscate and is calculated by dividing the product of the length squared and Pi by 4 times the area. The form factor provides information on the shape of a catchment and is expressed as the area divided by the length squared. Finally the basin elongation compares the longest dimension of the basin to the diameter of a circle of the same area as the basin and is achieved by dividing two times the square root of the area by the length times the square root of Pi. These ratios have been calculated based on the parameters previously mentioned and gathered from GIS. They are now commonly used in morphometric characterizations of sub-watersheds and basin environments (Vincy et al. 2012, Paul 2012), and are thought adequate by the authors to detail headwater catchment environments.

Table 3 shows a summary of the statistical results for each parameter, for 1st- and 2nd-order catchments. This information is further discussed below.

4. Discussion

4.1. Data

4.1.1. Catchments

Figure 2 shows a series of histograms together with associated cumulative curves. Divided between 1st-order catchments and 2nd-order catchments, this series concerns elevations (maximum and minimum), perimeters and areas, and, mean slope and mean orientation. All of them are related to the catchments. Histograms bins are not constant through Fig. 2, nor through Fig. 3 and Fig 4. They have automatically been determined to best fit the data (Shimazaki and Shinomoto 2007 A, B). The lower number of bins for the 2nd-order catchments is a consequence of a lower occurrence of 2nd-order catchments (Table 1).

The maximum elevation and minimum elevation histograms (Fig. 2) display a similar trend for catchments of both orders. Ranges spread from 0 and to just over 3000 m asl for both orders catchments maximum elevation; for minimum elevation 1st-order catchments values range from 0 to 2500 m asl when the 2nd-order catchments range from 0 and to just over 2000 m asl. The cumulative curve's shape changes depending on the parameter. For the maximum elevation, the cumulative curve presents for 1st-order catchments three clear inflection points (200, 400 and 1800 m asl) with a total cumulating abruptly reached. For the minimum elevation, the first inflection point is hardly distinguishable (same value as for maximum elevation). And the cumulative curve's maximum is reached more smoothly. For the 2nd-order catchments, the maximum elevation's cumulative curve shows two inflection points (400 and near 3000 m asl), and again finishes abruptly. For minimum elevation, two inflections points are seen on the cumulative curve (around 400 and 2500 m asl) and the shape of the curve is similar of that of 1st-order catchments. Maximum elevation's distribution is flatter than a Gaussian distribution and asymmetrical with a long tail to the left, although close from being symmetrical (Table 3). For minimum elevation, the distribution is flatter than a Gaussian distribution too, but the distribution is asymmetrical with a long tail to the right (Table3). The distributions do not change in function of the orders.

Area and perimeter are closely related, either for 1st-order or 2nd-order catchments. Lathrop and Peterson (1992) also acknowledged this relationship. It was no surprise that the histograms also accounts for this statement. Perimeters are found between 5 to 38 km for 1st-order catchments, and from just below 10 to around 55 km for 2nd-order catchments. The minimum area's value visualized for both orders catchments is due to the way they are defined in the GIS; a minimum of 1 square kilometre of draining area is used for defining the streams, and thus the catchments. Areas, starting thus at 1 km, reach 14 and 45 km^2 respectively for 1st-order and 2nd-order catchments, these values being coherent with past studies in the Pyrenees (Portilla et al. 2010). The cumulative curves also show the similarity in their relationship. One inflection point characterises the cumulative curves of both these parameters. Perimeter's inflection points are localised for 1st-order and 2nd-order catchments respectively at 15 and 30 km; area's inflection points at 5 and 17 km^2. Values for both parameters increase with the order. Area's distribution is more peaked than a Gaussian distribution, regardless of the order, and asymmetrical with a long tail to the right (Table 3). The distribution of the perimeter exhibits the same properties. Orders do not change the distributions shape.

The mean slope's cumulative curves show two inflection points for both orders: one around 17 degrees (°) and another one at 30°. From the same curve, more than half of 1st-order catchments has a mean elevation over 20°, and this value tends to increase with the 2nd-order catchments. Their range of value, somewhat wider for the 1st-order catchments, also differentiates 1st-order and 2nd-order catchments. For 1st-order catchments, values reach more than 40°, when this values is only nearly reached for 2nd-order catchments. The distribution of the mean slope, for both orders, is more peaked than a Gaussian distribution and asymmetrical with a long tail to the left, although close from being symmetrical (Table 3).

The Pyrenean range has a global orientation toward WNW-ESE. The histograms of the catchments mean orientation recognised this trend. Moreover the symmetry is striking, centred toward 170° (south being 180°). For both orders, two inflection points are seen on the cumulative curve; 120 and 240° for 1st-order catchments, and again 120 and 220° for 2nd-order catchments. The range is less wide for 2nd-order than for 1st-order catchments, just as observed for the mean slope. For both orders, the distribution of the orientation is more peaked than a Gaussian distribution and asymmetrical with a long tail to the right, although very close from being symmetrical (Table 3).

Differences between 1st-order and 2nd-order catchments are scarce when looking at this first series of parameters, related to classic morphometry. Except for parameters related to size (area and perimeter), values show similarities that offer little distinctions between 1st-order and 2nd-order catchments. Headwater catchments tend to be seemingly described by either both orders.

4.1.2. Streams

Figure 3 shows histograms related to a series of parameters extracted for each stream running within a defined 1st-order or 2nd-order catchment. The parameters studied here are length, average slope, 200 m slope, and outlet slope (Table 2). All those parameters are related to streams. Again the cumulative curve is represented above the histograms.

Stream length unsurprisingly increases with the order of the catchment where the stream is found. For 1st-order catchments, the maximum value reached is 14 km, and their isolation on the histogram could show the exceptional character of a few catchments. The cumulative curve, showing one inflection point, allows redefining another maximum obtained where the curve is flattening near the top. For the length, a value of 10 km emerges. It must be noted that more than half of the 1st-order catchments have a stream length superior to 1 km when, for the 2nd-order catchments, it nears 5 km. The isolated maximum closes 40 km, with less dispersion toward the maximum values than for the 1st-order catchments. For both orders, the distribution of stream length is more peaked than a Gaussian distribution and asymmetrical with a long tail to the right (Table 3).

Streams average slope's histograms are very similar in pattern. Like stream length's cumulative curve, it shows one inflection point. Again an isolated maximum is recognised for the 1st-order catchments, and again the dispersion seem to decrease with the order. If the isolated maximum is ignored, the maximum values are closer in range. However 1st-order catchments can be said to have little steeper slopes than 2nd-order catchments. This parameter slightly decreases with increasing orders. Rickenmann (1999) provides a range of values for channel's slope for clear water flows in his study of debris flows. It reports many different environments worldwide and the values presented herein agree with that of Rickenmann (1999), although lying at the lower end of its spectrum. Average slope's distribution is more peaked than a Gaussian distribution and, although being close from symmetrical, asymmetrical with a long tail to the right (Table 3).

Stream slopes have also been defined over 200 meters upward from their first intersection. Called the 200 m slope, the histograms show that for the 1st-order catchments the isolated maximum is over 40° and the secondary maximum nears 35°. Slightly more than half of those streams are under 5° over the last 200 meters. This value drops to 4° when 2nd-order catchments are considered, and the maximum is less than 30° (34° for the isolated maximum). The distribution of the data is more peaked than a Gaussian distribution and asymmetrical with a long tail to the right, regardless of the order considered (Table 3).

1st-order and 2nd-order catchments outlet slopes have maximums more pronounced than for all the other parameters. From 35° (non-isolated, 1st-order), it drops to 25 (2nd-order). (For the isolated maximum, 47° is reached for 1st-order, and it closes 35 for 2nd-order catchments) For both orders, the cumulative curve gives between 5° and 5.5° for a 50% accumulation. For both orders, outlet slope's distribution is more peaked than a Gaussian distribution and asymmetrical with a long tail to the right (Table 3).

When the streams are studied through the series of parameters presented above, the better distinction is found for the outlet slope, which is computed over a short distance. The distinction is poor when the stream is considered over a large distance. Moreover, the stream's length is dependant on the order, just like areas and perimeters, and likely to be biased by the 1 km^2 threshold used for defining the catchments.

4.1.3. Morpho-hydrological ratios

Morpho-hydrological ratios histograms and cumulative curves are shown in Fig. 4. Melton ratio, form factor, basin elongation and lemniscate ratio have been investigated and values are reported.

The Melton ratio (or ruggedness number) histogram for 1st-order catchments shows values reaching 1.5 as maximum, with a non-negligible portion over 1.0. Half of the 1st-order catchments have a Melton ration over 0.4. For the 2nd-order catchments, maximum values are not exceeding 1.0, and half of the 2nd-order catchments have a Melton ratio lower than 0.3. Due to its definition (Table 2), it is normal to find an isolated maximum, just like it was found for areas. Compared to other dataset gathered in the European and Southern Alps, the range of Melton ratio's values is coherent with past studies, although displaying less extreme high values (Bardou 2002; Welsh and Davies 2011). The role of the minimum area for defining the catchments on the Melton ratio's values is to be clarified, and could explain the values somewhat smaller observed in the study area. Concerning the distribution of the data, for both orders, it is more peaked than a Gaussian distribution and asymmetrical with a long tail to the right although close from being symmetrical (Table 3).

Form factor's histograms are very similar for both orders. Maximum values are found around 0.8, and minimum starts around 0.1. In both cases 0.4 seems to be the limit of the 50% accumulation when looking at the cumulative curve. The difference between catchments of 1st and 2nd order resides in the range, slightly less wide for the 2nd-order catchments. From Table 3, form factor's distribution is more peaked than a Gaussian distribution for both orders. It is also asymmetrical with a long tail to the right but very close from being symmetrical. The distributions are similar for both orders.

Basin elongation's histograms are again very similar for both orders. Starting at 0.3 (1st-order catchments) and 0.4 (2nd-order catchments), the maximum values do not reach 1.0. In both cases, half of the catchments have a basin elongation just under 0.7. Its distribution is more peaked than a Gaussian distribution and asymmetrical, although very close from being symmetrical (Table 3). However, for 1st-order, the distribution has a long tail to the right when, for 2nd-order, the long tail is on the left.

The lemniscate ratio, due to its definition (Table 2), presents histograms showing a minimum of 1.0. Again, the presence of an isolated and a secondary maximum is visible, again due to its equation based on parameters previously highlighting such a feature. For the 1st-order catchments, the isolated maximum is found at 8.5, when the secondary maximum seems to be close to 7.2. For 2nd-order catchments, these values are nearing 6 (isolated max.) and 5 (secondary). The shift toward the left observed here for the maximum values can also be seen when looking at the cumulative curve; half of the 1st-order catchments have lemniscate ratios below 2.1, and this value drops to 1.8 for 2nd-order catchments. For both orders, the distribution is more peaked than a Gaussian distribution and asymmetrical with a long tail to the right.

These ratios histograms mostly show little difference between orders. Basin elongation and form factor seem to be independent on the order, and remain almost unchanged, regardless the order of the catchments. On the other hand, Melton ratio and lemniscate ratio offer a wider range of values, and thus a better way to differentiate trends between catchments of different orders. However for all parameters, the cumulative curve's shape is unchanged through orders, either showing two inflection points (Melton ratio, Form factor and basin elongation) or just one (Lemniscate ratio).

4.2. Bi-dimensional comparisons

Parameters have also been compared between them through the edition of bi-dimensional graphs. Figure 5 shows six of these relationships taking into account the Pyrenean 1st-order catchments. The data is the same as used for the histograms presented above. When a correlation was obtained, a trend line is shown together with its equation and the R^2-value (Fig. 5 A, B and C). Otherwise, the graphs remain free of this information (Fig. 5 D, E and F). The parameters used are maximum and mean elevations, stream length, Melton ratio, area and mean orientation.

When the Melton ratio is plotted against the maximum elevation, it appears that the highest Melton ratio's values are found at higher elevation (Fig. 5 A). The ruggest catchments are found at high elevations. In Fig. 5 A, the best-fitting trend line is following a power law. The data could possibly be bracketed between two lines: an upper bound and a lower bound. Although not drawn, they are clear from the graph.

Figure 5 B shows the relationship that exists between area and stream length. Solyom and Tucker (2007) use this relationship in their work, which was probably first encountered in Strahler (1952) and his extensive analysis of erosional topography. The R^2-value is relatively high (almost 0.8) for this relationship best characterised by a linear trend line. In Leopold (1964), the same relationship is shown on a logarithmic scale, based on the work of Hack (1957). Rivers like the Ganges, the Rio Grande or the Nile, together with 31 other river basins, are plotted. The results concern much bigger areas and lengths than presented herein. The authors highlight a linear trend in their logarithmic scale between those two parameters, meaning that when compared to Fig 5 B, the trend line should follow a power law. In our case however, the trend is linear on a linear scale. Hack (1957), and then Leopold (1964) have studied one end of the spectrum, with high values of catchments orders (in fact, the highest order possible); the other end is presented here with 1st and 2nd-order catchments. The relationship could be linear near the beginning where values are low, and then become a power law, as values get higher. When the graph is edited for the 2nd-order catchments, it appears that the best fitting trend line is a power law (R^2-value equal to 0.49), when the linear trend gives one R^2-value equal to 0.47. It seems to confirm the change of the trend line with the change of values range.

Mean elevation and (streams) average slope are plotted in Fig. 5 C. The best-fitting trend line is a linear relationship and gives a low R^2-value. Figure 5 C shows that the highest slopes are found at high elevations, but the range of slope's values is wider given a certain high elevation; encountering a flat catchment is also likely at high elevations. To a lesser extent, Melton ratio behaves likewise (the Melton ratio is by some way a representation of the catchment's slope - Fig. 5 C is related to streams).

These two relationships indicate that tectonics and lithology may stronger influence catchments slopes and roughness than erosion. Figure 5 C, together with Fig. 5 A, reflects this fact. Restraining the fact that high slopes are found at high elevations because of erosion is to forget the influence of tectonic forces and material strength, of clear importance in mountainous environments. At high elevations, the erosional processes are more powerful (snow, wind, rain) and mountains material is more subject to erosion than at lower elevations where it accumulates.

Figure 5 also shows the mean orientation compared to the Melton ratio (D) and the stream length (E). The scatters are opposite. For the Melton ratio, it is seen that the maximum values are found at the edge of the scatter. The catchments are thus rugger when not facing the general orientation. As for the stream lengths, highest values are found for an orientation more consistent with the general trend of the range, as shown in the histogram.

The last graph presented in Fig. 5 is an example of two parameters that are not correlated in any way. The stream length seems not to be influenced by the elevation. Long streams can be found over the entire spectrum of elevations, and vice versa. It highlights the importance of the choice of the parameters in any study.

4.3. Regional distinctions

The Pyrenees are commonly compartmented in two main morpho-structural regions: the Axial Pyrenees and the pre-Pyrenees, which have been highlighted based on geology and tectonics (Fig. 1 A). Figure 6 shows for all 2nd-order catchments as many frequency curves as there are watersheds for three parameters: area (Fig. 6 A), mean elevation (Fig. 6 B) and Melton ratio (Fig. 6 C). 2nd-order catchments relationships and parameters were chosen for the readability of their graphs, as the same relationships for 1st-order catchments are very similar in trend. Table 1 gives a general distinction between watersheds in terms of mean values, when Fig. 6 actually graphically shows these distinctions evolutions.

In case of a poor regionalisation, watersheds cumulative curves are hardly distinguishable between each other, as shown for area (Fig. 6 A). The trends are similar no matter what is the watershed. A same value of area can be found in every watershed. The same comment applies also to perimeters, stream slopes, stream lengths or lemniscate ratio.

Figure 6 B is an example of a clear regionalisation. Based on mean elevation, it can be clearly distinguished and three trends are present. A first trend is defined by the cumulative curves of Fluvia and Ter (to a lesser extent) with a high frequency at low mean elevation decreasing with increasing mean elevation. A second trend is recognised when frequency increases with increasing mean elevation and the maximum in frequency found at high mean elevations, as exemplified by Garona and Valira’s cumulative curves. Eventually, lying between these two trends, are found the other watersheds cumulative curves. A distinction between these watersheds could be attempted based on frequency at high elevations, where Noguera Pallars and Noguera Ribagorçana in one hand, and Llobregat and Segre in the other, could be seen as displaying two distinct behaviours. Other elevations (maximum and minimum) cumulative curves follow a similar trend and induce similar distinctions.

As for the Melton ratio cumulative curves (Fig. 6 C), all shows a similar general trend: increase until a maximum and then slow decrease. However distinctions are possible in the light of the maximums position and the frequency at low Melton ratio's values. Fluvia and Ter cumulative curves display a maximum at very low Melton ratio's values (0.22). On the other hand, the other watersheds present a similar maximum in Melton ratios around 0.35. Out of these watersheds, two of them display a second maximum; for Garona the second maximum is found just over 0.6 in Melton ratio, and it is found around 0.74 for Valira. It is to be noted that those two watersheds cumulative curves are the only ones being null at low Melton ratio's values.

Garona, and Valira, could form one unique entity given the presented data. And Fluvia and Ter would be part of the last and lowest entity (low elevation and Melton ratio being representative). The rest of the watersheds would form the middle entity. If an attempt is made at naming these three entities, and identify the major behaviour of fluvio-morphological parameters for each watershed, one could distinguish between high-mountain, medium-mountain and low-mountain environments watersheds.

The comparison with the distinction giving Axial and pre-Pyrenees based on geology offers differences with the one presented herein. The Axial Pyrenees as defined in Fig. 1 consider watersheds that give very different geomorphological behaviours (Fluvia and Garona for example). If Valira and Garona are considered typical of high-mountain headwater watersheds, then the Axial Pyrenees cannot account for a high-mountain environment only whereas the regionalisation based on fluvio-morphological parameters could better differentiate headwater catchments and thus environments.

The data gathering was carried out at a given cell-size and with certain parameters. It was sought a description by the mean of parameters and not the statistical study of these parameters, nor the effect of a change in the cell-size. However, further investigation is required to precisely assess if a regionalisation is possibly hinted with the use and study of fluvio-morphological parameters. A statistical study looking at an ensemble of parameters could better refine the extent of such regionalisation and better emphasize at what scale would the regionalisation be optimized. Although high- and low-mountain environments are graphically distinguished, it could help apprehending and explaining the pre-Pyrenees and the disparities observed for the medium-mountain environment. It is shown here that using 2 common parameters, a distinction between Central-Eastern Pyrenean headwater catchments is recognised at a defined scale.

5. Conclusion

The morphometric analysis of Central-Eastern Pyrenean and Andorran catchments and streams has benefited from GIS techniques. The methods described herein allowed for the identification of a series of morpho-fluvial parameters related to either catchments or their constituent streams. These were used to investigate Central-Eastern Pyrenean headwaters, and more precisely 1st- and 2nd-order catchments and streams (according to Strahler's definition).

Some of the catchment-scale parameters, such as area and perimeter, were affected by the choice of the minimum draining area defined when digitalizing the catchments. The values for other parameters, such as elevation and mean orientation, were relatively unaffected. Furthermore, the values gathered in this study agree with those of past studies, showing that the 1-km^2 limit does not dramatically alter the values of the parameters. Stream and slope values gathered from the outlet and moving upstream were also obtained. Where slope was assessed, the smaller the stream segment, the more dispersion was observed. However, isolated values were found at the maximum end of the spectrum, which suggests the existence of abnormal catchments. Further study could help to explain their geomorphological meaning. Morpho-hydrological ratios mostly evolve in a similar way as the parameters defining them. These values also agree with past studies, thereby trivialising the difference between the minimum draining areas defining each catchment.

Bi-dimensional relationships are presented in the light of previous studies. The relationship between stream length and area is a power law relationship and is used for assessing large fluvial systems such as the Nile River (Leopold, 1964). The headwater catchments of the Central-Eastern Pyrenees represent the lower end of the spectrum and highlight how the relationship behaves near its origin. For the 2nd-order catchments of the study area, the power law and linear regression describe the relationship equally well (the R^2-values are similar in both cases). However, it was showed herein that the relationship is best fitted by a linear regression for 1st-order catchments. The evolution from a linear to a power law relationship as order increases needs further investigation.

As Leopold (1964) commented, the analysis depends how a catchment is defined. This study was carried out with a minimum draining area of 1 km^2, in a unique geological and climatic environment. However, as shown here, relationships can be applied globally.

Only a few large-scale morphometric studies of the Pyrenees have been undertaken, and when performed at catchment-scale, they focus on only a few parameters. This was a detailed geomorphometric analysis of 3005 Central-Eastern Pyrenean headwater catchments. Although requiring further refinement, these results can serve as a basis for risk assessment of natural hazards involving fluvial components, such as debris flows or flash floods.

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