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The hydrological significance of mountains. A regional case study: the Ebro River basin, NE Iberian Peninsula

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Abstract

This study evaluated the hydrological significance of mountain regions, comparison them with the lowlands of the Ebro River basin (NE Iberian Peninsula). It was based on records obtained from measuring stations. An altitude of 1000 m above mean sea level was adopted as the criterion for distinguishing between lowland and mountain areas. We analysed 12 sub-basins whose rivers flow directly into the River Ebro, and which covered 66% of the total surface area, 91% of the mountain area and accounted for 77% of total annual runoff. For the River Ebro basin, we found that the mean precipitation depth, the runoff volume per unit of surface area, and the runoff coefficient were all greater in the mountains than in the adjacent lowlands, with respective differences of 70%, 180% and 60%. These results and the particular fragility of the Mediterranean mountain ecosystems confirm the mountain regions of the Ebro basin as strategic zones for hydrological and territorial planning.

Key words mountain regions; mountain hydrology; water resources; Iberian Peninsula; Mediterranean river; River Ebro.

INTRODUCTION

Various recent studies, at both regional and world scales, confirm the determinant importance of mountain regions in the supply of hydrological resources to adjacent lowlands. This importance is manifested by the fact that the proportion of annual runoff contributed by mountain areas in the basins studied tends to be considerably greater than their proportion of the total surface area. For example, for 22 large basins distributed over several continents, Viviroli *et al.* (2003), Viviroli & Weingartner (2004) and Weingartner *et al.* (2007) showed that the average value of the quotient between the previously mentioned proportions was in the vicinity of 2.0-3.0. They also found that the value of this quotient was related to the type of climate. Maximum values were associated with basins with arid or semi-arid climates (in which the mountain region supplied between 50% and 90% of total runoff, with little seasonal variation), while values decreased as climates became more humid (with mountain regions supplying only 20% to 50% of total runoff, although with greater seasonal variation). In humid climates with a tropical influence, the average value of the coefficient even fell below 1.0. In a worldwide study, Viviroli *et al.* (2007) found that the hydrological and ecological significance of the world's mountain regions could be classified as being of essential (23% of the world's mountain area), supportive (30%), occasional (28%) or limited (19%) importance.

The greater hydrological relevance of mountain regions than their adjacent lowlands can be attributed to the greater quantities of precipitation that they receive (due to the effects of orography and elevation) and to reduced water losses due to evapotranspiration (because of

colder temperatures at higher altitudes) and infiltration (because of poor soils and steep slopes). Furthermore, mountain headwaters exert a notable regulatory effect on runoff, smoothing out seasonal variations as a result of spring and summer releases of precipitation accumulated in winter in the form of snow and ice.

One of the main pitfalls that research into the hydrological significance of mountain regions must overcome is the actual definition of the term “mountain”. In fact, there is no precise and universally valid definition of the term “mountain”, with local conditions being so diverse as to effectively undermine any attempt to propose a global standard. Furthermore, the criteria on which any proposed definition could be based, would tend to depend on the objective and discipline in question: geology, climatology, hydrology, ecology, botany, lithology, demography, economy, etc. Therefore, although it is normal for the principal criterion considered for the delimitation of mountain areas to be relative altitude combined with land slope, a series of other variables, such as the latitude, climate, continentality, geology, vegetation, accessibility, and/or variability of the hydrological regime in question, are also often considered.

Recent works on the hydrological importance of mountain regions, such as those by Viviroli *et al.* (2003) and Viviroli & Weingartner (2004), have adopted the pragmatic criterion of considering mountain regions to be places where the mean altitude above mean sea level (a.m.s.l.) is equal to, or greater than, 1000 m. In a global-scale study by Viviroli *et al.* (2007), all areas over 1000 m a.m.s.l. were included as mountain regions, as were those between 200

and 1000 m whose relief roughness exceeded 20‰. In the work of Weingartner *et al.* (2007), which focused on Switzerland, alpine basins were classified as being those where the mean altitude was greater than 1000 m a.m.s.l.

The objective of the research presented in this article was to evaluate the hydrological significance of mountain regions in relation to adjacent lowlands in the River Ebro basin (NE Iberian Peninsula), taking mean annual runoff recorded at measuring stations as a base for comparisons. Studies by Viviroli *et al.* (2003) and Weingartner *et al.* (2007) evaluated the river basin of the Ebro at the global scale. However, the particular circumstances of the global approach adopted in these studies (in terms of limitations in the availability of data and in the criteria employed for selecting representative measuring stations) undermined the validity of the results when greater precision was required, as amply explained in later sections. As a consequence, in this study, we sought to analyse hydrological significance on a smaller scale: at the level of the sub-basins of the direct tributaries of the main channel of the River Ebro. Furthermore, one of the objectives of this regional study was to check the findings of previous global studies relating to the River Ebro basin. Combining the results from the different sub-basins would make it possible to obtain an estimate of the significance of the mountain regions within the wider context of the whole River Ebro basin.

Study area

The River Ebro basin is situated in the northeast corner of the Iberian Peninsula, occupying a total surface area of 85 362 km² (Fig. 1). It is the most extensive river basin in Spain, the second largest in the Iberian Peninsula, and one of the largest hydrographical basins in the Mediterranean region. In general terms, the layout of the River Ebro basin resembles a trough that is bordered to the north by the Pyrenees and the Cantabrian mountain ranges, to the south by the Iberian range, and to the east by the Catalan coastal ranges. The low, relatively flat, area that lies between these mountain ranges is known as the Ebro depression. The basin forms a rough isosceles triangle with its base in the east, corresponding to the mouth of the river, and with its vertex at the source of the river (Fig. 1). The main drainage axis runs for 910 km in a northwest-southeast direction, between the Pyrenees and the Iberian range, although passing somewhat closer to the latter. Within this area, the spatial distribution of annual precipitation is related to relief (with most precipitation being recorded in the peripheral ranges that enclose the basin) and to distance from oceanic influences. Mean annual precipitation varies from over 2000 mm in the Pyrenees to less than 400 mm in the arid interior. The rainfall regime is characterised by inter-annual irregularity, especially in the central area of the depression, and by seasonal contrasts. The trough-like layout of the basin also influences the thermal conditions. The temperature moderating effect exerted by the oceans is limited to the western half of the northern mountain fringe. In the rest of the basin, and especially in the depression, a marked degree of continentality is observed, which translates into high summer temperatures and intense winter cold. The mean annual potential

evapotranspiration of the basin is 700 mm (Thornthwaite method), while in the central depression, the mean annual value is approximately 800 mm, and in the mountains ranges of the basin, this value is around 600 mm.

Fig. 1 Location of the study area.

The *Confederación Hidrográfica del Ebro* (CHE) (Hydrographic Confederation of the Ebro) is the government agency responsible for managing the water resources of the River Ebro basin. According to this agency (CHE, 2005), the mean annual water yield of the River Ebro basin under a natural flow regime is around 18 km³. The mean annual runoff reaching the sea as registered at the measuring station located at the mouth of the River Ebro, is approximately 12 km³. The difference, i.e. 6 km³, approximately coincides with the mean annual water consumption of the basin. However, in over recent ten-year periods, annual

water consumption has been closer to 8 km³ and therefore the annual volume of water discharged into the sea has been around 10 km³. Irrigation for agriculture clearly stands out as the most important use responsible for withdrawing water from the system (approximately 90%), while the other withdrawals basically correspond to meeting urban and industrial requirements. Energy production (and especially that of hydroelectric power) is the most significant form of non-withdrawal demand, with 41 km³. Of the approximately mean annual 12 km³ discharged into the sea, around 3 km³ are destined to cover the ecological needs of the final reach of the River Ebro. The main aim of Spain's National Hydrological Plan is the implementation of an inter-basin annual water transfer of up to 1 km³ from the lower Ebro valley to the north and south Mediterranean coast. This transfer has been prompted by pervasive pressures, scarcity, and the degradation of other river basins in south-east Spain (Albiac *et al.*, 2006). However, various reasons, including the appearance of a conflict of interests between regions, possible damage to the natural environment (Ibañez & Prat, 2003) and the emergence of new socio-cultural values (Tàbara & Ilhan, 2008), have made it impossible to apply the planned inter-basin water transfer.

The River Ebro and its tributaries are regulated by over 187 dams, with a total capacity equivalent to approximately 60% of total mean annual runoff. In series of long term records, changes in mean annual runoff were detected after the construction of some of dams, with a predominant trend towards diminution (Batalla *et al.*, 2004). According to Ibañez *et al.* (1996), 22% of the decrease in mean annual runoff can be attributed to reservoir evaporation and 75% to irrigation. The distribution of the water yield between river banks is characterised

by asymmetry, with the contribution of the largest tributaries on the Pyrenean side of the river representing 78%, while the main tributaries on the right bank only contribute 15%.

According to the least favourable hypotheses, global change could leave the Ebro basin with a rather precarious hydrological equilibrium between its resources and demands. On one hand, a reduction in the level of available hydrological resources has been predicted as a result of a future fall in annual precipitation and increase in mean annual temperature in the course of the present century (e.g. López-Moreno *et al.* (2008) estimate a fall in precipitation of up to 15% in the Pyrenees range and a concurrent increase in temperature of up to 4 °C). On the other hand, an increase in the withdrawal demands of up to almost 10 km³ has been predicted, which is basically related to an increase in the demand for irrigation. If we also consider the current annual water demand to meet the ecological needs of the lower course of the River Ebro (3 km³) and the annual volume planned for the inter-basin transfer (up to 1 km³), the net result at the end of the 21st century would be an insignificant surplus of annual water resources.

MATERIAL AND METHODS

We started by delimiting the different sub-basins of the River Ebro that were to be analysed. The general criterion adopted for the delimitation of the study sub-basin involved including all the direct tributaries of the main stream of the River Ebro. An exception was made in the cases of the rivers Segre and Cinca, which were considered separately. This was justified by

the fact that both have large basins and because the River Cinca flows into the River Segre very near to the point at which the latter joins the River Ebro.

Each sub-basin was subsequently divided into two areas, with one corresponding to the mountain area and, by logical exclusion, the other corresponding to the lowlands. As explained in the previous section, delimiting the mountain areas was no easy task. In this study, we adopted an altitudinal threshold of 1000 m a.m.s.l. as the practical criterion for distinguishing between lowland and mountain areas; this same criterion had been adopted by other researchers in previous studies (e.g. Viviroli *et al.*, 2003; Viviroli & Weingartner, 2004). This was justified in the case of the River Ebro basin given the maximum altitude of the surrounding mountain ranges and the relatively low density of high altitude measuring stations. Sub-basins with inexistent or negligible surface areas lying at altitudes above 1000 m a.m.s.l. were candidates for exclusion from the study. For the same reason, we also excluded all interfluvial areas and any other terrain of relatively minor importance from which waters drained directly to the main stream of the River Ebro. Given the fact that the sub-basins that were candidates for exclusion from the study were basically located in lowland areas, it would be reasonable to assume that this could introduce an element of bias into the global estimation for the River Ebro basin. Such exclusions were therefore only made when the impact on the global result was negligible.

From a theoretical point of view, the total water yield of a sub-basin should be determined using records from a measuring station located at the mouth of that sub-basin and its

confluence with the River Ebro. Likewise, the water yield of the mountain area should theoretically be defined by the sum of the contributions recorded at measuring stations located at the intersection of the drainage network with the 1000 m a.m.s.l. contour line. While, in general, there were measuring stations located sufficiently close to the outlet of each sub-basin, there was evidently not a measuring station at every point in the drainage network with an altitude of 1000 m a.m.s.l.

This presented us with the problem of having to choose the most suitable measuring stations in order to obtain a representative idea of the mountain region in each sub-basin. We were aware that if the chosen stations were located at altitudes of less than 1000 m a.m.s.l. values for mountain runoff would be overestimated, as runoff from lowland areas would be attributed to mountain areas. On the other hand, if the chosen stations were located above that altitude (or if there were no measuring stations located in any of the branches of the mountain drainage network) another error would be committed, as part of the runoff contribution of the mountain area would not be recorded. In the definitive selection of the measuring stations that best characterised each sub-basin, we selected the combination which seemed likely to minimise any potential error. In doing this, however, we always bore in mind the fact that it was preferable for any potential error resulting from omission from the whole of the mountain area (error by defect) to be greater than the potential error resulting from the incorporation of part of the lowland area (error by excess), as this was more conservative with regard to the study hypothesis.

Four sources of information were consulted in order to determine the spatial distribution of mean annual runoff in the Ebro basin, select the measuring stations most suited to the objectives of the research, and check the data available from a given station (Justribó, 2006). These sources were: (a) the records of the *Red Oficial de Estaciones de Aforo* (ROEA) (Official Network of Measuring Stations) of the *Confederación Hidrográfica del Ebro* (CHE), which are available for the period 1912-2001 (CHE, 2006-b); (b) data from the measuring stations included in the proposal for the *Plan Hidrológico de la Cuenca del Ebro* (PHE) (Hydrological Plan for the Ebro Basin), which are available for the period 1960-1993 (CHE, 1996); (c) estimates of annual discharge under a natural flow regime, taken from the proposal of the PHE and based on records, from the period 1940-1986 (CHE, 1996) and (d) estimated annual discharge under a natural flow regime based on the Sacramento model and records, from the period 1940-1991 (CHE, 2006-c).

For mountain measuring stations, the four data sources mentioned showed high levels of concordance and we generally used the data obtained from the ROEA. Conversely, in the case of the measuring stations chosen to represent the hydrological contribution of the whole sub-basin, important divergences were observed between different data sources. Firstly, for some of the smaller sub-basins, there was no measuring station either at its mouth or at a neighbouring upstream site. Furthermore, when these were available, the volume of annual discharge measured tended to be lower than that registered at stations located further upstream (and in some cases, it was even lower than that measured at stations located in the heart of the mountain area). In general, this can be explained by the diverse derivations of

withdrawal use. One option for dealing with this problem would have been to quantify the relative significance of these mountain areas, in a way that reflected their individual circumstances. This could have been done, for example, by comparing the proportions of the hydrological contribution of these mountain areas with totals for sub-basins, which in some cases would have exceeded 100%. In fact, this methodology has been adopted in some other studies (e.g. Weingartner *et al.*, 2007). Nevertheless, in this study, in order to calculate the global discharge of the sub-basins, we used the database of estimated annual discharge under a natural regime presented in the proposal of the PHE, which gave an increased volume of mean annual runoff downstream.

Altitude data was obtained from the Digital Elevation Model of the Ebro basin (CHE, 2006-a), which has a spatial resolution of 100 m. Long-term averaged annual precipitation data were obtained from a contour map, drawn up using historic pluviometric information (with the data including an updated series until the year 2002) obtained from more than 3000 stations belonging to the Spanish Meteorological Agency. Almost 1600 of them were located inside the basin itself, while the rest were scattered across the neighbouring area. In order to assess the water balance in Switzerland (divided into sub-basins at the regional scale), Weingartner *et al.* (2007) proposed calculating precipitation for a given area using runoff, evaporation and changes in water storage, instead of derived it from gauged precipitation values. In this way, they sought to avoid potential errors deriving from a reduction in the density of the precipitation stations and the increase in precipitation with increasing altitude. However, we considered that using this methodology in the River Ebro basin would not offer

any significant advantage as the information on the spatial distribution of some of the cited components (and particularly that of actual evapotranspiration) is significantly less accurate than that relating to the precipitation.

In order to evaluate the hydrological significance of the mountain area compared to the lowlands, and to study the variables that most influenced this significance, we developed a number of different indices. In general, these indices compared the respective proportions of these different variables in mountain and lowland areas.

In order to check whether precipitation was highest in the mountain regions of each sub-basin, the precipitation index (I_P) was defined as

$$I_P = (P_m/A_m)/(P_l/A_l) = (P_m/P_l)/(A_m/A_l) \quad (1)$$

where P_m and P_l respectively represent the volume of mean annual precipitation in the mountain and lowland areas of the sub-basin and A_m and A_l are the respective surface areas of the mountain and lowland areas of the sub-basin. Values of I_P greater than 1.0 indicated a greater proportion of precipitation in the mountain area than in the corresponding lowland area.

In order to check the relevance of the mountain region of each sub-basin in comparison with its associated lowland area with regard to annual runoff contribution, the index of water yield (I_Y) was defined as

$$I_Y = (Y_m/A_m)/(Y_l/A_l) = (Y_m/Y_l)/(A_m/A_l) \quad (2)$$

where Y_m and Y_l respectively represent the mean annual runoff volumes in the mountain and lowland areas of the sub-basin. Values of I_Y more than 1.0 indicated a greater proportion of hydrological contribution from the mountain area than from the corresponding lowland area.

In order to compare the runoff coefficients of the mountain (C_m) and lowland (C_l) areas, the index of runoff (I_R) was defined as

$$I_R = C_m/C_l = (Y_m/P_m)/(Y_l/P_l) = (Y_m/Y_l)/(P_m/P_l) \quad (3)$$

Values of I_R more than 1.0 indicated a greater runoff coefficient in the mountain area than in the corresponding lowlands.

Seeing that other researchers frequently analysed the relevance of the mountain area in relation to the whole of the sub-basin, in order to facilitate comparisons with previous studies, we also defined the index of water yield (I_S) in relation to the whole sub-basin

$$I_S = (Y_m/A_m)/(Y_s/A_s) = (Y_m/Y_s)/(A_m/A_s) \quad (4)$$

where Y_s and A_s respectively represent the mean annual runoff volume in the sub-basin and the surface area of the sub-basin surface area. Values of I_S more than 1.0 indicated that the proportion of runoff from the mountain region with respect to the whole sub-basin was greater than its area with respect to the area of the whole sub-basin.

In order to check the relationship between climate and the hydrological significance of the mountains previously reported by other researchers on a worldwide scale, we correlated our

I_Y value for each sub-basin with the De Martonne aridity index (I_A) (which depends on mean annual values of precipitation (P in mm) and temperature (t in $^{\circ}\text{C}$): i.e. $I_A = P/(t + 10)$).

RESULTS AND DISCUSSION

Fig. 2 shows the 12 sub-basins of the River Ebro basin which were finally selected for the present research. Table 1 specifies the percentage of the total surface area of the River Ebro basin represented by the surface area of each of the selected sub-basins (S_E) and the percentage of the total sub-basin area represented by what could strictly be defined as mountain area (i.e. that located at an altitude of over 1000 m) (S_m). The sum of these sub-basin values accounted for 66% of the total surface area of the River Ebro basin, 91% of the total mountain area of the basin and 77% of its mean annual runoff.

Fig. 2 Sub-basin analysis and selected mountain measuring stations.

Table 1 Selected sub-basins within the River Ebro basin. Ordered by their order of confluence with the River Ebro following the direction of flow.

Sub-basin	Abbreviation	S_E (%)	S_m (%)	S_{mg} (%)
Tirón	T	1.5	32.5	24.1
Najerilla	N	1.3	57.1	49.0
Iregua	I	0.8	74.7	84.1
Leza	L	0.6	54.4	52.1
Cidacos	C	0.8	52.6	56.5
Aragón	A	10.1	20.2	14.5
Jalón	J	12.0	44.7	39.4
Gállego	G	4.7	23.0	18.5
Martín	M	2.5	24.9	27.2
Guadalope	Gu	4.6	45.1	55.5
Cinca	Ca	11.5	26.7	20.5
Segre	S	15.3	40.6	41.1
Total	Ebro	65.6	35.1	32.2

There were various reasons for excluding the remaining sub-basins from our study: the absence of measuring stations; a lack of measuring stations suitable for the purposes of this study; an insufficient proportion of mountain area within the sub-basin in question ($< 2\%$). Strictly speaking, it was therefore not possible to apply the indices defined by equations (1)-(4) to the whole River Ebro basin. Nevertheless, we considered that the proportion of the total territory represented by the sum of the 12 sub-basins selected for total area, mountain area and annual runoff in relation to the basin as a whole was sufficient to justify their combination and use to represent the behaviour of the whole of the River Ebro basin. The sub-basins with proportions of mountain regions equivalent to less than 2% of their total area and which also had their own measuring stations respectively represented only 2.4% of the total area of the

River Ebro basin and 3.5% of its mean annual water yield. In order to evaluate whether the contributions of these sub-basins were significant or not, within the scope of the present study, we analysed the change in the value of I_s index when these measurements were included and excluded.

Table 1 shows the percentage of each sub-basin's surface area that corresponded to its reference mountain measuring station (S_{mg}). The differences between values for S_{mg} and S_m imply an error in the estimation of the respective proportions of mountain and lowland areas in the different sub-basins. Fig. 3 represents the percentage of the total surface area with an altitude of more than 1000 m a.m.s.l. in each of the selected sub-basins whose runoff could not be recorded by measuring stations considered to be representative of the mountain area in those sub-basins. It also represents the percentage of the total surface area with an altitude of less than 1000 m a.m.s.l. whose runoff it was impossible to exclude from the records of mountain measuring stations. Hence, the higher the percentages of these two areas, the greater the error that would tend to result when estimating the ratios between mountain and lowland areas in each sub-basin. For the majority of the sub-basins studied, we considered several options according to the combination of the different mountain measuring stations that were selected as being representative. Fig. 3 presents values for the options that were finally chosen: the combinations that produced the smallest estimated global error. As can be seen, in most cases the first set of percentages was greater than the second, which would constitute a conservative result for demonstrating the prevalence of the hydrological contribution of the mountain area.

Fig. 3 Percentage of area with an altitude of more than 1000 m a.m.s.l. excluded, and percentage of area with an altitude of less than 1000 m a.m.s.l. included in the records of measuring stations representing the mountain area of each sub-basin.

As a first step towards studying the significance of mountain regions, we represented the respective percentages of the mountain and lowland areas for each sub-basin in relation to total area and mean annual volume of precipitation and runoff (Fig. 4). In this figure it can be seen that for most of the sub-basins, the proportion of precipitation volume was notably higher and, above all, that mountain area runoff was higher than the percentage of the total area that the mountain occupied in the whole sub-basin.

The I_P value calculated, for each of the selected sub-basins using equation (1) is represented in Fig. 5. With only two exceptions (those of the Guadalupe and Iregua) the sub-basins had index values of more than 1.0, which corroborated the greater precipitation per unit of surface area received in the mountain area than in the corresponding lowlands. For a combination of the 12 sub-basins studied, we obtained an average value of $I_P = 1.7$, which, in the absence of better information, could be considered representative of the whole River Ebro basin.

Fig. 4 Proportion of area and volume of precipitation and mean annual runoff in the mountain areas and lowlands of each sub-basin.

In the theoretical case of the mountain areas generating more runoff than the lowlands for a given value of precipitation depth (i.e., their runoff coefficient being higher), the value of I_Y would increase with respect to I_P . This was the case for most of the sub-basins studied, as can be seen from comparing Figs. 5-a and 5-b (where the I_Y value in the latter was calculated according to equation (2)). This confirms the hydrological significance of mountain regions.

The combined value for the whole Ebro basin increased from $I_P = 1.7$ to $I_Y = 2.8$. The relationship between the runoff coefficients of the mountain and lowlands areas is represented in Fig. 5-c, according to values calculated applying equation (3). This figure reveals that I_Y values of more than 1.0 can not only be explained by the greater precipitation received in the mountain regions, but also by their greater efficiency in generating runoff. In this case, the explanation lies in the lower evapotranspiration occurring in the mountain areas (Rodríguez *et al.*, 1996).

Fig. 5 Relationships between the proportions of mountain and lowland areas in relation to: (a) volume of precipitation and the area of each sub-basin; (b) volume of runoff and the area of each sub-basin; (c) volumes of precipitation and runoff in each sub-basin. (d) Relationship between the proportions of mountain territory and the whole sub-basin with regard to runoff volume and the area of each sub-basin.

Mountain ecosystems are important suppliers, regulators and maintainers of natural and cultural resources. The values obtained from the indexes proposed for assessing the sub-basins of the River Ebro (Fig. 5) confirm the relevance of mountain areas for the generation of water resources (in terms of the amount of mean annual precipitation received and the quantity of runoff generated). Although mountain ecosystems are characterised by their rich diversity, they are also distinguished by their high degree of ecological fragility (mainly due to severe climatic conditions and gravitational denudation processes). They are susceptible to accelerated soil erosion, landslides and rapid losses of habitat and genetic diversity. This is particularly true of mountain regions with Mediterranean climates (McNeill, 1992). Mountain basin protection and management is considered strategic by most Mediterranean countries, and has been one of the main reasons for protecting upland forests and implementing large-scale afforestation programmes (Regato & Salman, 2008).

In order to facilitate comparisons between this study and previous works by other authors, the hydrological significance of the mountain regions was also expressed in terms of the relationship between the proportions of annual runoff and area for both the total mountain area and the whole sub-basin. The I_s value calculated according to equation (4) is presented in Fig. 5-d. We obtained values greater than 1.0 for most of the sub-basins and an average value for the whole River Ebro basin of $I_s = 1.8$. By including sub-basins with percentages of mountain areas of less than 2%, the value of I_s was reduced from 1.77 to 1.75 under the hypothesis that all of the runoff generated in them could be assigned to the lowlands. In other

words, Fig. 5-d would not be modified (i.e. $I_s = 1.8$). As a result, it was finally decided not to include these sub-basins when calculating the different indexes for the whole basin.

The value of $I_s = 1.8$ is very similar to that obtained by Viviroli *et al.* (2003) and Weingartner *et al.* (2007) for the River Ebro (i.e. $I_s = 1.9$). Their value was calculated as the quotient of 57% of the annual runoff and 30% of the total area located above 1000 m a.m.s.l. In accordance with the information provided by Viviroli *et al.* (2003), the River Ebro basin was globally analysed using data from measuring stations located in Castejón and Tortosa, which were respectively taken as being representative of the mountain region and the whole basin. However, using the Castejón station as a characteristic reference for the mountain region of the whole River Ebro basin is hardly appropriate at the regional scale. Although the Castejón station records 57% of the mean annual runoff (48% in terms of the natural flow regime) which is drained from a surface area corresponding to approximately 29% of the River Ebro basin, only 21% of this surface area is located above 1000 m a.m.s.l. represents only 26% of the mountain area in the whole of the River Ebro basin (and, furthermore, excludes the parts of the Pyrenees which are most extensive and highest in altitude). Moreover, in Viviroli *et al.* (2003) and Weingartner *et al.* (2007), the authors estimated seasonal variations in I_s for the Ebro basin whose values ranged from approximately 1.2 to 2.3; these values could also be questioned for the reasons already explained.

In Weingartner *et al.* (2007), four groups of large basins from various continents were classified according to the hydrological significance of the mountain regions in relation to

their corresponding lowlands. These authors included the River Ebro basin (along with the basins of the rivers Saskatchewan, Columbia and Wisla) in the third group, which was characterised by an I_s value of around 2.0, although this value was subject to seasonal variations due to the contribution of melt waters from spring thaws. It is important to point out that, except for the River Ebro basin (which was classified as semi-arid), all the other basins in this group are located in regions with humid climates.

According to the De Martonne aridity index, the climate values for the 12 sub-basins selected ranged from semi-arid (18 mm °C⁻¹) to humid (45 mm °C⁻¹). As the areas with the most humid climates coincided with the mountain ranges surrounding the basin and the most arid region was the central depression, the gradient of the aridity index approximately followed the direction of the main streams of the sub-basins studied and decreased as they progressed downstream. The correlation between I_Y and the De Martonne index for the 12 sub-basins exhibited a low explanatory power ($R^2 = 0.38$) and the trend observed was even the opposite of that found in other studies, as the I_Y value increased as the climate got more humid. This may have been due to the contrast between the local climates of the River Ebro's sub-basins not being as marked as those between other basins contrasted at world scale.

CONCLUSIONS

In this research, the criterion adopted for distinguishing between lowlands and mountain areas was the 1000 m a.m.s.l. In keeping with this criterion, 12 sub-basins were selected, 11

of which were direct tributaries of the River Ebro. These sub-basins represent 66% of the total surface area of the River Ebro basin, 91% of the whole mountain area of this basin, and 77% of its mean annual runoff. We considered that these proportions justified combining the 12 sub-basins of the River Ebro to provide an approximate representation of the average behaviour of the whole river basin. The remaining sub-basins were mainly excluded because of the lack of measuring stations that suited the aims of this particular study.

In 10 of the 12 selected sub-basins, it was confirmed that the mean annual precipitation per unit of area in the mountain region was greater than that in the lowlands. On average, for the whole River Ebro basin, the former was 70% greater than the latter ($I_P = 1.7$). In 11 of the 12 sub-basins studied, it was confirmed that the mean annual runoff per unit of area in the mountain region was greater than in the lowlands. On average, for the whole River Ebro basin, it was estimated that the former was 180% greater than the latter ($I_V = 2.8$). This was because besides the fact that the mountain regions receive more precipitation than the lowlands, their runoff coefficient is also higher. In the case of the Ebro basin, this coefficient is 60% greater in the mountain region than in the lowlands ($I_R = 1.6$). This disproportionate generation of runoff in mountain regions is also patent when we consider that although the mountain area only represented 32% of the total surface area of the Ebro basin studied in this research, it was responsible for 57% of its mean annual runoff ($I_S = 1.8$). These results, together with the singular fragility of Mediterranean mountain ecosystems, confirm that the mountain regions of the River Ebro basin are areas that require special attention, both in terms of specifically hydrological planning and territorial planning in general.

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