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FLOODPLAIN OCCUPATION AND FLOODING IN THE CENTRAL PYRENEES

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ABSTRACT. *Floods modify the natural dynamics of river environments and greatly affect urban areas, especially in mountain regions where flooding is frequent because of the precipitation characteristics and orographic configuration. In this study the vulnerability of the central sector of the Pyrenees to flood events was investigated using frequency analysis of daily flow and precipitation data for the period from 1940 to 2012 for the headwaters of the Aragón and Ésera rivers. The land use evolution over the past 60 years was also analyzed. The return periods showed that floods have not been exceptional, and the high flow frequency has been large and closely related to precipitation events. This, combined with a large increase in human occupation, particularly since the 1990s, of fluvial areas associated with the land use evolution since 1956, has increased exposure to flood risks.*

Ocupación de la llanura aluvial e inundaciones en el Pirineo Central

RESUMEN. *Los ríos modifican la dinámica natural del ambiente fluvial y afectan enormemente a las áreas urbanas, especialmente en áreas de montaña donde las precipitaciones son frecuentes debido a las características de la precipitación y a la configuración orográfica. En este artículo se analiza la vulnerabilidad del sector central de los Pirineos a estos eventos, a través de un análisis de frecuencia de los datos de caudal y precipitación diarios desde 1940 hasta 2012 en las cabeceras de los ríos Aragón y Ésera. Se analiza también la evolución de los usos del suelo en los últimos 60 años. Los periodos de retorno muestran que las inundaciones no son excepcionales y que la frecuencia de caudales elevados es alta y estrechamente relacionada con los eventos de precipitación. Este hecho, combinado con un excepcional crecimiento de la ocupación humana de las áreas fluviales (especialmente desde la década de 1990) producida por la evolución de los usos del suelo desde 1956, ha aumentado el riesgo actual de exposición.*

Key words: floods, vulnerability, Pyrenees, Aragón and Ésera rivers, regional planning.

Palabras clave: inundaciones, vulnerabilidad, Pirineos, Río Aragón, Río Ésera, planificación regional.

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1. Introduction

Floods occur relatively frequently in mountain areas of the Iberian Peninsula, particularly the Pyrenees. These flood events have been the subject of a number of studies, especially at sites in the eastern Pyrenees (e.g., Llasat *et al*., 2008, 2010) and the Central Range (e.g., Ruiz Villanueva *et al*., 2010, 2013; Ballesteros *et al*., 2011). In the central Pyrenees major studies have focused on specific events, including the Biescas campsite disaster in 1996 (García Ruiz *et al*., 1996; Gutiérrez *et al*., 1998).

The high frequency of extreme precipitation and flash floods in Mediterranean areas is well established (Marchi *et al*., 2010; Llasat *et al*., 2014), and may be increasing consistent with climate change projections (Madsen *et al*., 2014).

The high level of hazard associated with extreme flood events is because of the speed with which they occur and the flow conditions, which are characterized by high velocity, significant water depth, and high sediment yields (Díez Herrero *et al*., 2008; Ollero, 2014). The risks are exacerbated where particularly vulnerable land uses occupy the alluvial plain, particularly residential areas, campsites, and main roads.

The Pyrenean range is a high risk area for these types of event because of the evolution of land use in recent decades, which has increased exposure and vulnerability (García-Ruiz and Lasanta-Martínez, 1990; Beguería *et al*., 2003, 2006; Gallart and Llorens, 2004; López-Moreno *et al*., 2006; García-Ruiz *et al*., 2008).

The hydrological year 2012/2013 was notable for two extreme precipitation and flash flood events in the central Pyrenees, which occurred in October 2012 and in June 2013, respectively. These events caused major damage to river channels, banks, and floodplains where new land uses including urban areas and main roads had been established during preceding decades.

The aim of the present study was to characterize the evolution of risk exposure in the headwaters of the Aragón and Ésera rivers in the central Spanish Pyrenees. To this end we conducted statistical analyses of hydrological data and their relationship to climatic data. We identified the most significant events, and compared these with the evolution of land use over the past 60 years. Areas previously belonging to fluvial land use types were quantified. This change has led to greater exposure to flood events, and demonstrates that the increased risk has been a consequence of inadequate regional planning in recent decades.

2. Data and methods

2.1. Study area

The study area included the headwaters of the Aragón and Ésera rivers, where the precipitation and flash flood events of October 2012 and June 2013 noted above occurred, respectively. The study area comprises two zones, both of which are on the southern slopes of the Pyrenees, inside the Ebro basin and near the French Atlantic watersheds. The headwaters of the Aragón River are between the western and central sectors of the Pyrenees, while the upper Ésera River is more clearly in the central sector, further from coastal influences. Both watersheds show similar characteristics. The relief is very pronounced in each headwater. The Ésera River headwater has the most summits exceeding 3000 m a.s.l. in the entire Pyrenean range, with the highest peak being Aneto (3404 m a.s.l). The headwaters of the Aragón River reach 2300 m a.s.l at the source and 950 m a.s.l in the valley where Villanúa is located (Fig. 1). The length of the river in the study area is approximately 8.5 km, over which there is a change in elevation of some 170 m; the river ends just downstream of the town of Castiello de Jaca. The Ésera River, which receives meltwater from the Maladeta glacier, arises at 2800 m a.s.l, and extends less than 17.5 km to Castejón de Sos (875 m a.s.l).

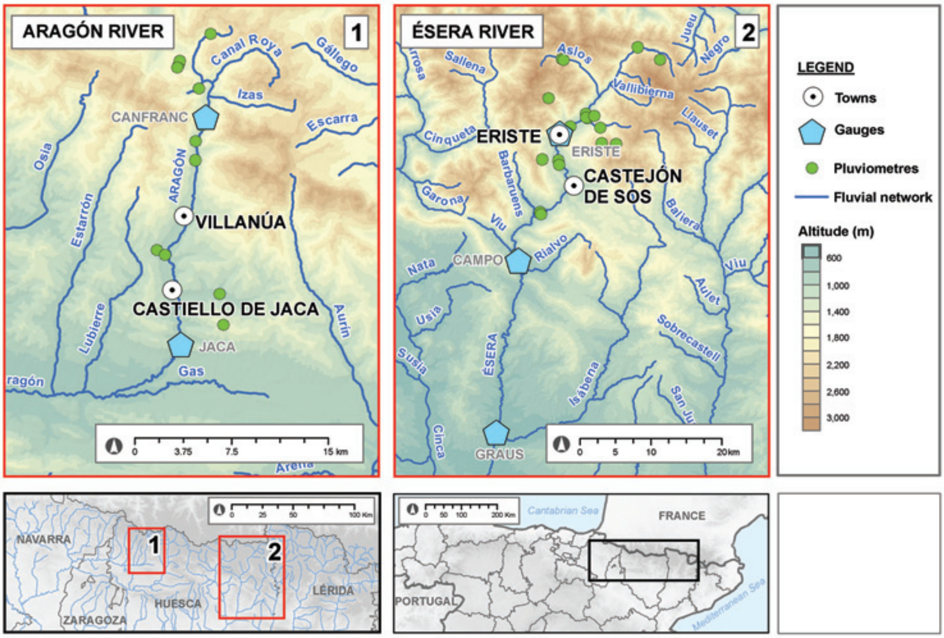

Figure 1. Study area.

The urban areas of Villanúa and Castiello de Jaca in the Aragón River watershed, and Eriste and Castejón de Sos in the Ésera River watershed, have increased in size over recent decades, and now occupy floodplain areas and in some cases the riverbed. This has increased hazard risk, which despite the effects of recent flooding has still not been reduced. The census population, which does not necessarily include all inhabitants, has increased in all the study localities over the last few decades, and between 1991 and 2011 the number of houses increased by 76% in Villanúa and 289% in Castiello de Jaca (Table 1). In these towns houses owned as second residences represent more than the half of the total, reaching 88% in Villanúa.

Table 1. Inhabitants (P) and housing (V) according to the population census. The percentages of second residences over the total is shown in parentheses.

Town	1991		2001		2011	
	P	V	P	V	P	V
Villanúa	283	1076 (90.1%)	340	1558 (88.6%)	495	1900 (87.9%)
Castiello de Jaca	139	154 (51.9%)	188	374 (78.6%)	250	600 (76.7%)
Eriste (Sahún)	315	232 (55.6%)	286	388 (40.7%)	325	465 (66.7%)
Castejón de Sos	449	313 (41.9%)	617	451 (37.7%)	745	800 (57.5%)

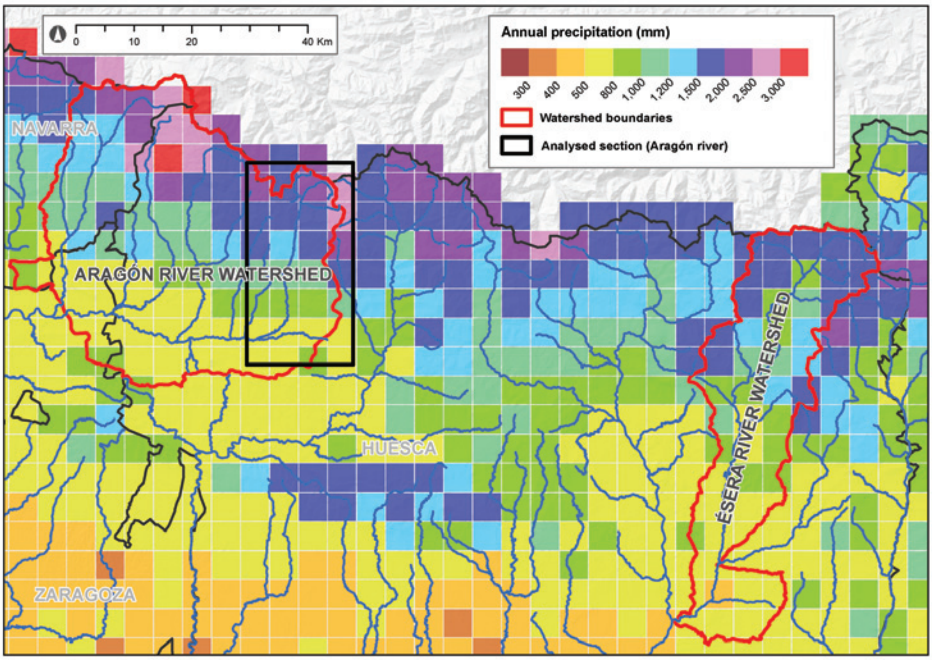

Figure 2. Mean annual precipitation in the headwaters of both watersheds (Serrano-Notivoli et al.*, in preparation).*

The two watersheds receive from 500 to more than 2500 mm annual precipitation (Fig. 2), and show a clear altitudinal gradient of increasing precipitation with elevation. In the highest sections of the Aragón River, precipitation can exceed 3000 mm (Serrano-Notivoli *et al*., in preparation); this is one of the locations in Spain that receive the highest levels of annual precipitation because of a combination of high elevation and a strong Atlantic Ocean influence. Convective precipitation events are relatively frequent in the summer and autumn months, and can produce large amounts of rainfall in 24 hours or less. These events result in sudden increases in the flows in ravines that feed the main rivers, and cause flash flooding.

2.2. Precipitation and flow

To detect relationships between precipitation and flow during extraordinary flood events we used daily data from 37 precipitation stations (16 in the Aragón basin and 21 in the Ésera basin; Fig. 1) over the period 1940 to 2012. To obtain a continuous dataset over the entire period, a quality control process was applied to the original data, and any gaps were filled using multivariate logistic regression based on reference values. The reconstruction process used to obtain complete daily precipitation series is fully described by Serrano-Notivoli *et al*. (2017).

A comprehensive hydrological database was used to analyze flood events. The database included data from 1930, which were only available in the longest series, while data for 2012 were included in most of the series. Data were extracted from many sources (Table 2). Average flows at various temporal scales were used to characterize the flood types. Hourly data were used to analyze some specific events. The datasets for six gauging stations were incomplete (Table 3), but the missing data values were not reconstructed as the aim was to identify extreme events and not to reconstruct the flows.

Table 2. Source and types of hyrological data used in the analyses.

Source	Type of data
Gauging Yearbook System (SAA)	Daily, monthly and annual mean flow. Maximum instantaneous flow (monthly and annual)
SAIH-Ebro	Hourly flow event 2013 and historic flows
National Catalogue of Historic Floods (CNIH)	Historical flood effects
National System of Floodable Zones Cartography (SNCZI-IPE)	Maximum flows maps

Maximum instant flows at monthly and annual scales can indicate floods in headwaters and facilitate the analysis of the frequency, magnitude, and seasonal distribution of extreme events. The Maximum Flows Map, extracted from the National System of Floodable Zones Cartography (Sistema Nacional de Cartografía de Zonas Inundables: SNCZI) (http://www.magrama.gob.es/es/agua/temas/gestion-de-los-riesgos-de-inundacion/snczi/) was used to estimate the maximum flow values corresponding to the study area, based on the methodology developed by CEDEX (2011). To supplement the results we also applied the Gumbel distribution, which is typically used to define extreme value recurrence periods in both climatic and hydrological situations (Gandulis, 2003; Overeem *et al.,* 2008; Ben-Zvi, 2009; Koutroulis and Tsanis, 2010; Yang *et al.,* 2010; Moncho *et al.,* 2012; Serinaldi and Kilsby, 2014).

Table 3. Gauging stations, and data available through the Gauging Yearbook System.

River	ID	Name	Altitude	Period	% Gaps
Aragón	9164	Canfranc	1165 m	1971–1991 (21 years)	2.25
Aragón	9271	Canfranc	1040 m	1991–2012 (22 years)	0.42
Aragón	9018	Jaca	793 m	1930–2012 (83 years)	1.78
Ésera	9145	Eriste	830 m	1951–2012 (62 years)	0.11
Ésera	9258	Campo	675 m	1992–2012 (21 years)	2.29
Ésera	9013	Graus	450 m	1931–2012 (82 years)	4.44

We chose periods when the flow at each gauging station was 25-fold greater than the daily mean discharge (15-fold in Eriste and Campo in order to detect more events), and for those selected events we computed the number of times that precipitation exceeded the historic 1940–2012 mean for all observatories upstream of the gauging stations involved. We also reviewed the National Catalogue of Historical Floods (Catálogo Nacional de Inundaciones Históricas: CNIH) to establish the main and most frequent effects of these events.

2.3. Diachronic cartography

For the land use analysis we mapped the zones most affected by recent flood events (October 2012 and June 2013) by geo-referencing aerial photographs from 1956 and 1957 (American flight B-Series) and from 1973 to 1986 (Inter-ministerial flight: 1981–84), and also used orthophotographs obtained in 2012 (National Plan of Aerial Orthophotography: PNOA). From these we identified an area 250–500 m from the channel limit matched with most sensitive areas to derive a contour that was homogeneous and comparable among all dates. The cartography was discretized in categories directly related to fluvial dynamics (water, sediment bars, and riverside vegetation), those related to human occupation (crops, urban areas, and the category *human intervention* in 2012 maps), and other uses (shrub and bush) that generally occur further from the main channel.

Although the river course was mapped, we expanded at a greater scale four specific zones coinciding with the urban zones of Castiello de Jaca and Villanúa in the Aragón River watershed, and Eriste and Castejón de Sos in the Ésera River watershed. These zones have been subject to major changes over the last 50 years, and are the most exposed to flood risk.

3. Results

3.1. Magnitude and frequency of historical floods

The hydrological series from Jaca (Aragón River) shows that from 1946/47 to 2011/12 there were 19 monthly maximum instantaneous flows that were 25-fold greater than the mean annual flow, with three of these exceeding the mean annual flow by more than 40-fold, and one exceeding it by more than 50-fold. The majority of these extraordinary flood events occurred in October, November, and June.

For the same time period at Graus on the Ésera River we extracted the maximum instant flows that exceeded the mean annual flow by 25-fold (7 events) and more than 50-fold (1 event). The monthly spreading in these cases was greater than for the Aragón River at Jaca. Most of these events occurred in autumn and the beginning of summer.

The return periods defined by the SNCZI, and those computed using the Gumbel distribution using the maximum instant flows, were consistent in the longest series and differed for gauges near the headwaters (Table 4). These discrepancies increased as the return period increased, especially for the Ésera River watershed, which indicates that the reliability of these calculations was very low for the most extreme events. This was probably because of the uncertainty of these return periods and the length of the flow series.

Table 4. Return periods at each gauge using SNCZI and Gumbel.

		Method	2 years	5 years	10 years	25 years	100 years	500 years
Aragón river	Canfranc	SNCZI	134	194	243	332	485	698
		Gumbel	46.7	67.6	81.4	98.9	124.7	154.5
	Jaca	SNCZI	136	206	265	365	564	854
		Gumbel	127.2	199.1	246.6	306.7	395.6	497.9
Ésera river	Eriste	SNCZI	204	316	416	597	927	1390
		Gumbel	78	200.2	281.1	383.3	534.5	708.4
	Campo	SNCZI	222	355	476	700	1123	1725
		Gumbel	213.9	363.4	462.4	587.4	772.3	985.1
	Graus	SNCZI	257	417	559	814	1323	1976
		Gumbel	231.4	392.5	499.2	633.9	833.1	1062.4

In this context, the last significant flood in the Aragón River (October 2012; Acín *et al.,* 2012) had a very short return period at Canfranc (approximately 7 years), but a very long return period at Jaca (> 100 years). The June 2013 flood in the Ésera River (Serrano-Notivoli *et al*., 2014) had a return period of approximately 10 years.

References to specific effects of historic floods in the Aragón River headwaters are found in the CNIH (Table 5). Detailed information is available for the November 1982 flood. In this case the towns most affected were located in the headwaters, river defenses and power lines were damaged at Jaca, and a large sediment discharge was recorded at Villanúa. CNIH references to the Ésera River over the last three decades (1998, 2001, 2007) indicate major impacts, mainly evacuations even with no major peak flows. This may be because of an emphasis on precaution, and probably use of the floodplain for campsites. In addition, damage was reported to houses, orchards, poplar plantations, roads, irrigation canals, and power lines. The damage produced by Ésera River floods was worsened by the effect of tributary ravines.

Table 5. Historic floods recorded in Aragón and Ésera watersheds.

Watershed / Source	Date	Effects
Aragón / CNIH	1787 (Sep), 1927 (Jul), 1937 (Oct), 1952 (Feb), 1963 (Jul-Ago), 1971 (Apr), 1974 (Mar), 1979 (May-Jun), 1982 (Nov), 1997 (Nov)	High flows, intense precipitations and/or ice melting, overflow and damages in riversides, effects on infrastructure and towns such as Jaca or Villanúa.
Ésera / CNIH and SAIH-Ebro	1907 (Oct); 1937 (Oct); 1960 (Jul); 1963 (Jul-Ago); 1965 (Nov); 1976 (Oct); 1982 (Nov); 1984 (Nov); 1997 (Nov); 1997 (Dic); 1998 (Sep); 2001 (Ago); 2007 (Ago)	Benasque flooded basements in 1925, isolated in 1963. Other towns repeatedly affected are Eriste, Villanova, Castejón de Sos, Seira and Campo.

Floods in the Aragón River (Fig. 3) showed rapid evolution, in most cases had a similar length of direct flux (basic time) and exceptionally, the peak unfolded in two, or the depletion curve showed multiple oscillations.

Hydrographs for the Ésera River (Fig. 4) showed three types of floods. Those that occurred in autumn evolved rapidly (1960, 1963, 1965, 1982, 1997), those in spring had longer and more complex evolution (1966, 1971, 1977), and those in summer had short and rapid evolution (1960, 1963). The flood episode in June 2013 was similar to those that occurred in spring, but the flood was longer and less complex because precipitation had a greater influence than melting.

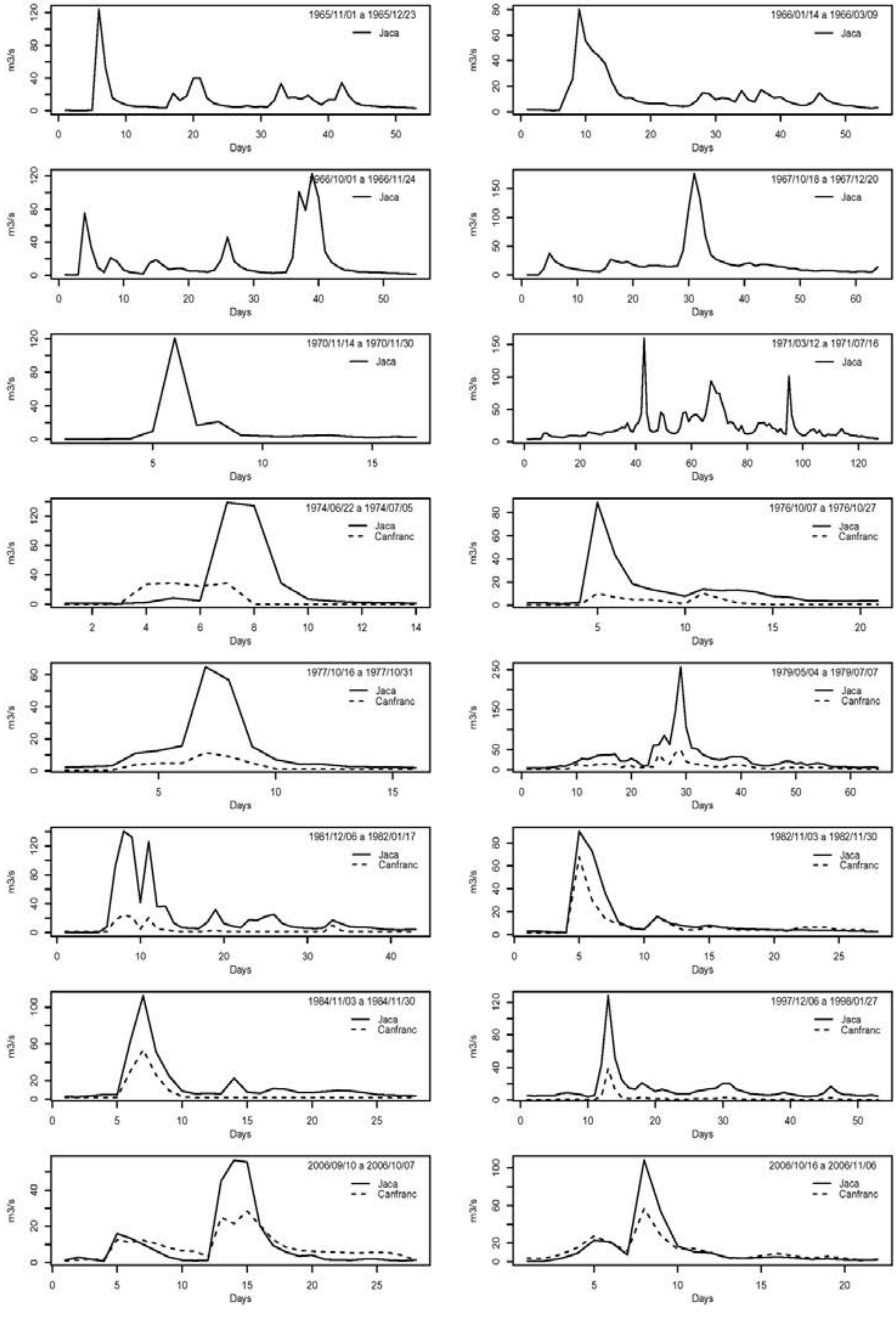

Figure 3. Hydrographs of floods over 25 times the annual mean in Aragón River.

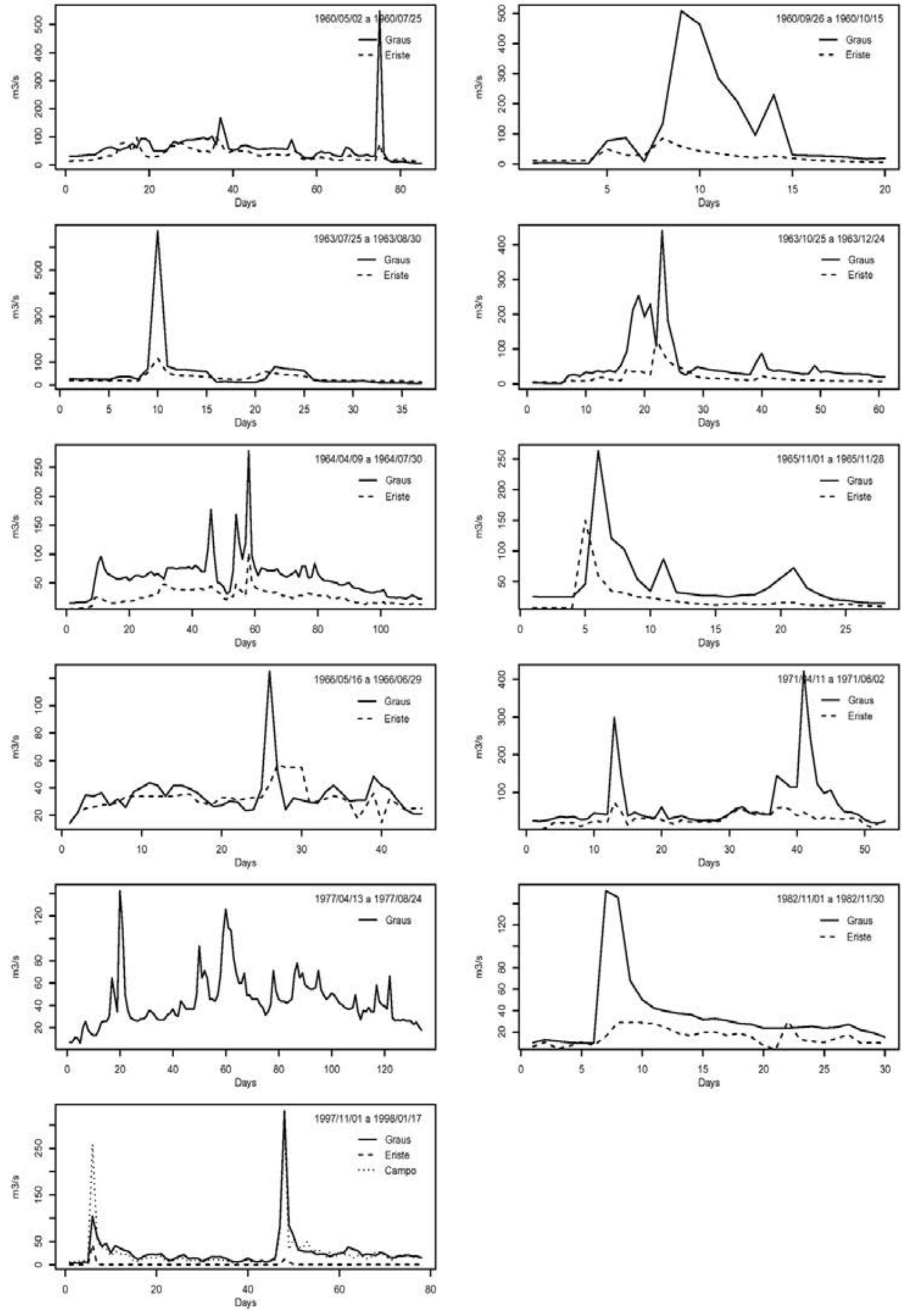

Figure 4. Hydrographs of floods over 25 times the annual mean in Ésera River.

3.2. Magnitude of recent floods

None of the historic events reached the discharge recorded in October 2012 at Canfranc (74.3 m^3/s) or Jaca (635 m^3/s) (Acín *et al*., 2012) (Fig. 5, upper panel).

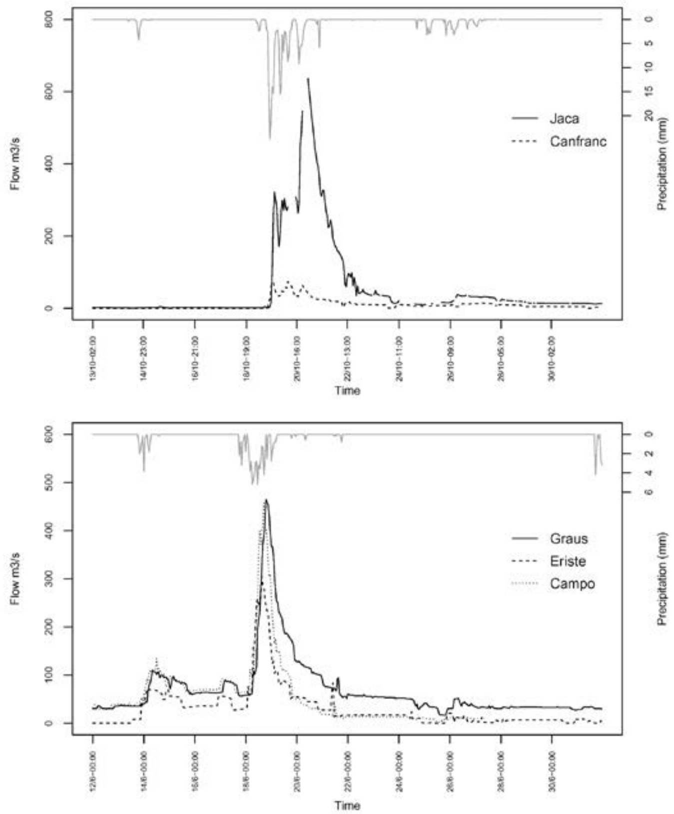

Figure 5. Hydrographs of October 2012 flood on the Aragón River (upper panel) and June 2013 on the Ésera River (lower panel).

The hydrograph corresponding to the Aragón River flood in October 2012 was consistent with the general dynamics of the headwaters during Aragon River floods. However, the rising curve took longer to reach a peak (which almost reached the highest values previously recorded), and showed a rapid rise in flow from noon on 19 October. This rising *saw tooth* curve was very pronounced for Jaca, and was related to the characteristics and intensity of precipitation. The peak was reached at 8:00 AM on 20 October at Canfranc (74.38 m^3/s) and Jaca (635 m^3/s; maximum historical record). For Jaca there were some discontinuities in the records for the early morning of 21 October.

The increase of flow in the Ésera River in June 2013 was directly related to precipitation that commenced at 6:00 PM on 17 June, and which was preceded by other minor precipitation events on 14 June. The flow increased very rapidly from early on 18 June (Fig. 5, lower panel), and peaked in the afternoon (Eriste: 304.9 m^3/s; Campo: 460.7 m^3/s; Graus: 464.57 m^3/s).

Between 18 and 19 June the curve declined, creating an extended depletion curve. The flood was short and had a great displacement speed. The times that elapsed from the peak in precipitation intensity until the flood flow peaks at Eriste, Campo, and Graus were 10, 12, and 14 h, respectively. Thus, the peaks were recorded with a 2-hour delay from each gauging station to the next. Among previous peak flow discharges at both Eriste and Campo, on only one occasion was the peak flow of this flood exceeded.

3.3. Precipitation-flow relationships

The extraordinary increases in flow were mostly related to extremely high precipitation events. In the Aragón River the most intense floods (which account for > 40% of annual mean flow) were associated with daily precipitation exceeding mean precipitation by a factor of 15–20 (Fig. 6, upper panel). Nevertheless, in the case of the highest level of precipitation recorded (October 2006), the flow almost exceeded the mean flow by 30% (Fig. 6, upper panel).

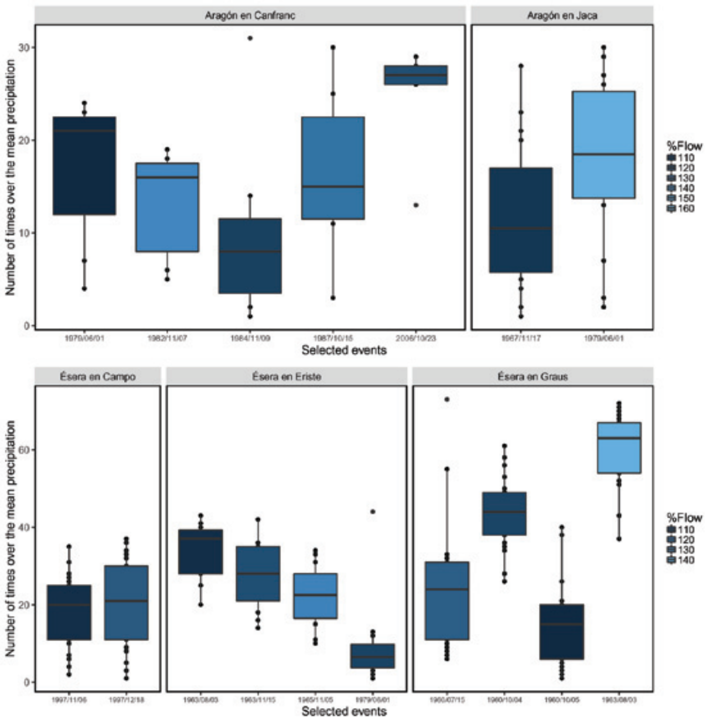

Figure 6. Number of times in which precipitation upstream of the gauging stations was greater than the historic mean (1940–2012). Colour scale indicates the percentage of flow over the annual mean.

The Ésera River responds more directly to precipitation. In almost all extraordinary flood events the precipitation was > 20-fold the mean daily value; in the biggest flood recorded, in August 1963, the precipitation event led to a discharge that was 60-fold greater than the mean value (Fig. 6, lower panel).

The relationship between precipitation and flooding is not direct because the causes of floods vary, and the prior conditions in the basin vary substantially from one flood to another. The flood events that occurred at the end of spring were in most cases more related to the combined processes of precipitation and snowmelt. Therefore, these floods occurred over a longer time period, and were not necessarily triggered by extreme precipitation events.

3.4. Land use changes

Land use analysis of the alluvial plain in both watersheds showed a pronounced decrease in the area occupied by natural environments.

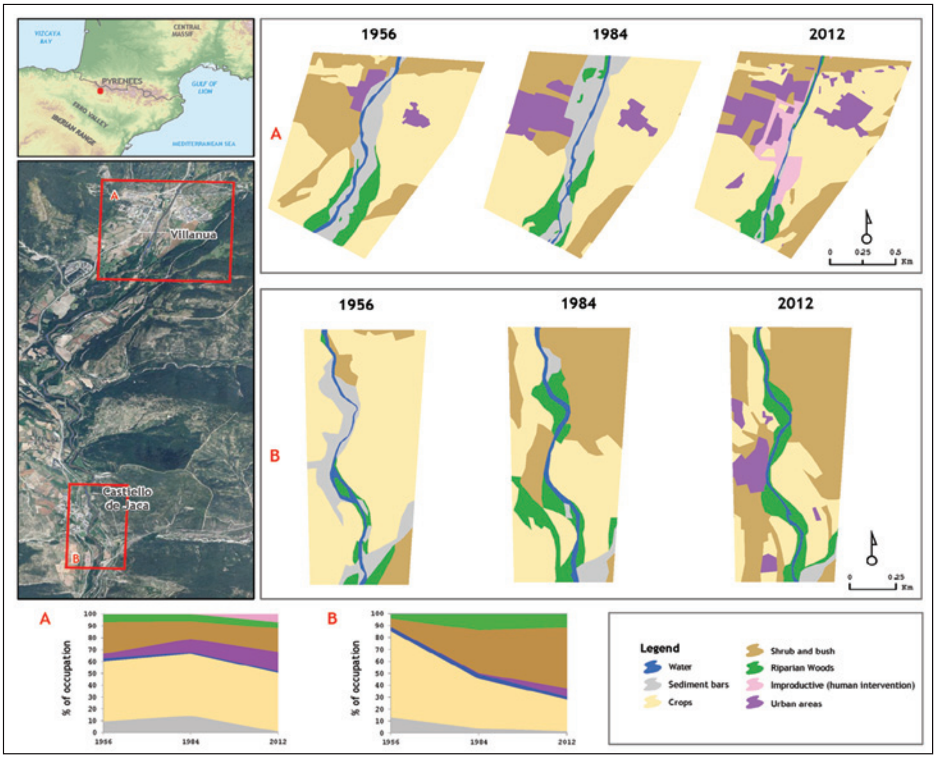

Figure 7. Temporal evolution of surface land uses along the Aragón River.

In the case of the Aragón River (Fig. 7A) the natural fluvial areas in the town of Villanúa accounted for up to 22% of the total surface area at the beginning of the 1980s, whereas it now occupies < 8% of the area. The decline in the area occupied by sediment bars has been dramatic, declining from > 14% in 1981 to slightly > 1% in 2016. The areas of water bodies and riparian vegetation have not changed significantly. Conversely, urban areas have increased from < 4% in 1956 to > 16% in 2012; an additional approximately 7% of the area has been affected by human intervention, comprising areas not strictly urbanized but subject to human use.

The same trend has occurred at Castiello de Jaca (Fig. 7B), where the fluvial areas decreased from 22% in 1956 and the 1980s to a little more than 15% in 2012, with the area of sediment bars decreasing from 13% in 1956 to 1.5% in 2012. The areas of water bodies and riparian vegetation have also decreased in recent decades, but to a lesser extent than for sediment bars. The increase in urban areas has been considerable, from a non-significant proportion of the surface area until the 1980s to almost 7% in 2016. A similarly large change in the land use category "crops" to "other vegetation" has also occurred, probably related to the abandonment of farms and the revegetation of these areas.

The changes in the Ésera River valley have followed a similar pattern to those described for the Aragón valley. In the Eriste area (Fig. 8A) sediment bars covered > 10%

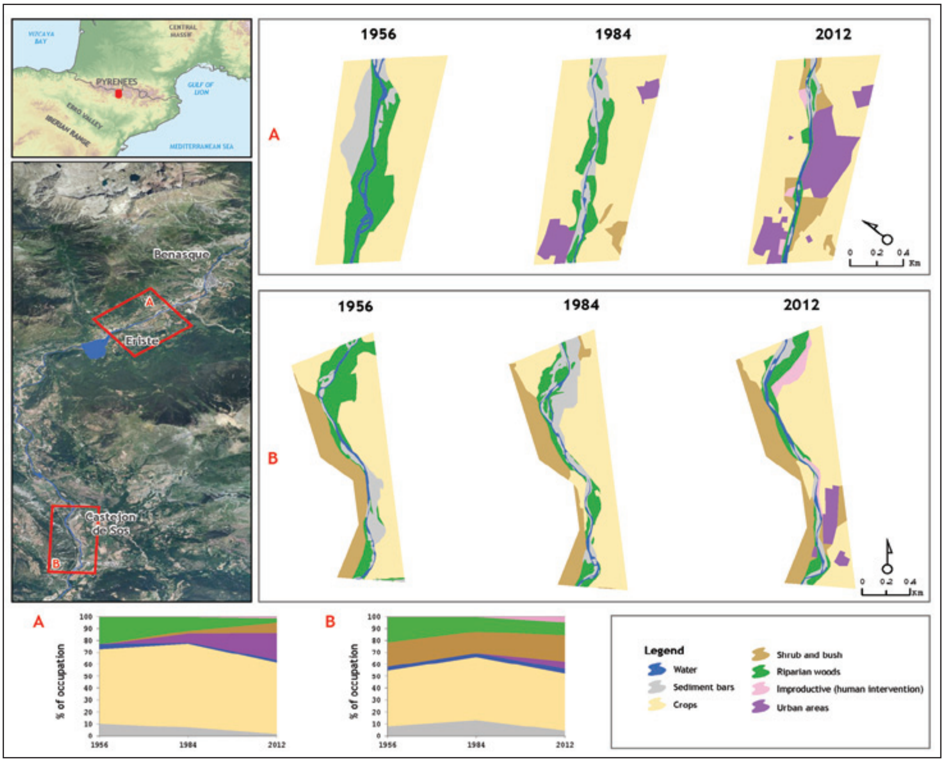

Figure 8. Temporal evolution of surface land uses along the Ésera River.

of the total area in 1956, while in 2012 they represented only 2%. Riparian vegetation declined from 23% in the middle of the 20th century to approximately 4% in 2012. During the same period urban areas increased from a very low level to > 8.5%. These urban zones broadly occupied areas that were formerly fluvial natural spaces. There was also a remarkable increase in the area of the category "other vegetation", associated with a reduction in cultivated areas resulting from land abandonment.

The same spatial pattern is evident for Castejón de Sos (Fig. 8B). The sediment bars, representing a natural fluvial environment, underwent the greatest decrease, declining from 13% of the total area in the 1980s to < 4.5% in 2012. The area occupied by riparian vegetation has declined to almost half of that in 1956, and urban area increased from being almost non-existent to accounting for 6% of the total area in 2016. In this case, the remaining categories appear stable.

During recent decades many land use changes have occurred in both watersheds, resulting in loss of the natural character of the riverine areas and an increase in more urbanized areas subject to flooding. This represents a high flood risk and an exponential increase in vulnerability.

4. Discussion

The occurrence of extreme hydrological events in the central Pyrenees in recent years has not been correlated with atypical external factors, but with normal hydro-meteorological processes in the mountain range, or at least events having normal and short recurrence periods. Previous studies in the same area have shown that the most extreme flood events were related to very high levels of precipitation (García-Ruiz *et al*., 1983; Martí Bono and Puigdefábregas, 1983; Plana-Castellví, 1984; Clotet *et al.,* 1989; Corominas and Alonso, 1990). However, the additional risk caused by floodplain occupation has resulted in greater vulnerability, especially in urban and suburban areas.

Floods in the central Pyrenees between 2012 and 2013 produced major damage, although they were not associated with increased hazard (in terms of flow) relative to previous events. The fact that two extreme events occurred so close together in time does not necessarily imply that there is a trend of increase in extreme events. Nevertheless, this possibility should be the subject of future analysis.

The well-established human occupation of these fluvial systems and the increased debate about post-flood measures are novel elements compared with previous events. Indeed, the vulnerability of this area is the factor most responsible for the increase in risk and damage.

This analysis of risk highlights issues including the usefulness of return period comparisons. The differences that occur among the computing methods, despite use of the same data, increase uncertainty about their use. Because of this the generalized use of SNCZI values must be treated cautiously, and only used as an indication, as small changes in hydrological and hydraulic simulations and calibration methods (which evolve over time) can completely change the final results and their interpretation.

Previous experience and scientific reports show that only for regions having very regular precipitation and long historical records (not the case for the present study area) is the estimation of return periods relatively reliable (Beguería and Lorente, 1999). Consequently, it would be unwise to base post-flood measures on return periods. The last two events reactivated hydro-geomorphological fluvial processes, generating major damage to the human environment, particularly the road network and urban uses (Acín *et al*., 2012; Serrano-Notivoli *et al*., 2014). This highlights a problem that has developed and steadily increased during recent decades, namely occupation of the alluvial plain or fluvial areas by land uses that are vulnerable to floods and the natural processes of erosion and river channel movement. Flood events in rivers that are artificially re-routed demonstrate that the defenses constructed to avoid damage to fields and infrastructure are easily eliminated or breached, suggesting their ineffectiveness when exposed to high-intensity hydrological events.

A scientific and technical debate is developing concerning post-flood treatments. From various scientific and environmental viewpoints (for instance, the Professional Association of Geographers and the Iberian Centre for Fluvial Restoration) it is considered preferable to accept the action of the river during floods in channel resizing and self-regulation to achieve effective flood evacuation, with human land-uses having to adapt to the new hydro-geomorphological conditions. Nevertheless, government agencies responsible for river basin and road management have usually rapidly implemented emergency works to restore streams to their previous paths and conditions through expensive channeling work, with no environmental control. Scientists and environmentalists have been very critical of these measures, which undermine the natural behavior of the streams and alluvial plains (which in this case are declared Sites of Community Importance i.e. SCI ES2410046: the Ésera River; and SCI ES2410021: headwaters of the Aragón River), and destroy the riverbed and riverside morphologies and the sedimentary deposits left during flood events. It is highly doubtful whether these measures, which contradict European Union legislation (Water Framework: 2000/60/EC; Floods: 2007/60/EC; and Environmental Impact: 2011/92/EC), will decrease the hazard. Conversely, they potentially promote a false sense of security among the population and could encourage new urban developments in high risk areas.

The social and media impact of the management of risk is of great importance. However, the subject usually lacks scientific input, although there have been recent contributions from the field of geography (Olcina, 2008, 2009; Gonzalo *et al*., 2010; Sánchez Fabre and Ollero, 2010; Vinet, 2010, Conesa and Pérez, 2014; Ollero, 2014).

These extreme events have been useful for the development of hazard and risk maps required under Directive 2007/60/EC, which in Spain is integrated in the SNCZI. Not all river environments have been mapped, although the fluvial stretches affected by the Pyrenean floods considered in this study have been included, and their characteristics have served to update and adjust the maps. However, to date this has not resulted in land management and planning restrictions. In fact, the October 2012 event at Castiello de Jaca (Aragón River) resulted in the demolition of a house and considerable damage in the *El Molino* residential zone, and buildings were damaged in the *Linsoles* residential zone during the June 2013 event at Benasque (Ésera River). In both cases the inhabitants were allowed to reoccupy their properties without any restriction. Only the camping area at Castejón de Sos, which was also affected by the June 2013 event, was closed and dismantled.

5. Conclusions

A recurrence analysis was carried out to assess the vulnerability of the central Pyrenees to flash floods. The main conclusions were as follows.

In the Aragón River catchment, 16 flood events in which the flow exceeded the mean annual flow by > 25-fold were identified between 1940 and 2012. Eleven of these events occurred in autumn and four in spring. These floods developed rapidly, and the event having the greatest flow occurred in October 2012.

In the Ésera River catchment, 11 flood events were identified in the 1940–2012 period. In excess of 50% of these occurred at the end of spring or the beginning of summer, coinciding with snowmelt periods.

The October 2012 flood was correlated with intense autumn precipitation in the headwaters of the Aragón River, and a rapid concentration of flow in the streambeds. The June 2013 episode in the Ésera River was correlated with a typical spring flash flood, although precipitation contributed a higher proportion of the discharge input than did snowmelt. The extensive socio-economic damage that resulted in each alluvial plain was probably a result of inappropriate human occupancy of the fluvial area.

Analysis of precipitation associated with the most extreme historical flood events confirmed that they were related to periods when precipitation greatly exceeded average values, especially in downstream sections of the headwaters at Jaca (Aragón River) and Graus (Ésera River). In the latter case, precipitation twice exceeded the daily mean by 50-fold.

Land use change analysis showed that in the last 60 years human activity in the river floodplains has increased, increasing vulnerability of populations, human activities, and infrastructure to flash flood events. It is noteworthy that the decline in the area occupied by sediment bars in the Ésera and the Aragón valleys (9% and 13%, respectively) indicates that the most geomorphologically active fluvial areas have been largely turned over to human-related uses.

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