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DENDROGEOMORPHOLOGICAL EVIDENCE OF FLOOD EVENTS IN THE UPPER CATCHMENT OF THE NOGUERA PALLARESA RIVER (PYRENEES, SPAIN)

Evidencias dendrogeomorfológicas de inundaciones en la cuenca alta del río Noguera Pallaresa (Pirineos, España)

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ABSTRACT: Mountainous areas are prone to torrential floods that are characterized by their ability to mobilize large volumes of sediment and other materials such as large wood. In the case of the upper catchment of the Noguera Pallaresa River (Pyrenees of Lleida, Spain), the main destructive floods are well identified and their main parameters described, but the detailed spatial and temporal edge of these and other less severe events are still lacking. With the aim of extending the information on the effects of these floods, this work analyzes and compares different data sources, based on dendrogeomorphological sampling carried out in two tributaries of the Noguera Pallaresa River: the Flamisell River (on the right-hand margin) and the Romadriu River (on the left-hand margin). The dating of the main dendrogeomorphological indicators in both these tributaries, especially scars and abrupt growth changes, and also the estimated dates of tree establishment, are contrasted with data from the documentary, geomorphological, meteorological, and hydrological sources. It is verified that in these small and medium subcatchments, with very heterogeneous rainfall due to orography, the instrumental data (often very scarce) may not adequately reflect the hydrological dynamics. This work confirms that an analysis of the dendrogeomorphological and documentary sources is therefore essential to characterize and evaluate the incidence of these torrential floods in different territorial areas.

KEYWORDS: Torrential Dynamics, Tree Rings, Instrumental Records, Historical Data, Geomorphological Analysis, Romadriu, and Flamisell Subcatchments.

RESUMEN: Las zonas montañosas son propensas a inundaciones torrenciales que se caracterizan por su capacidad de movilizar grandes volúmenes de sedimentos y otros materiales como troncos y otras piezas de madera de gran tamaño. En el caso de la cuenca alta del río Noguera Pallaresa (Pirineos de Lleida, España), las principales inundaciones destructivas están bien identificadas y descritos sus principales parámetros, pero aún falta el detalle espacial y temporal de éstos y otros eventos menos severos. Con el objetivo de ampliar la información sobre los efectos de estas inundaciones, este trabajo analiza y compara diferentes fuentes de datos, a partir de muestreos dendrogeomorfológicos realizados en dos afluentes del río Noguera Pallaresa: el río Flamisell (en el margen derecho) y el río Romadriu (en el margen izquierdo). La datación de los principales indicadores dendrogeomorfológicos en ambos afluentes, especialmente cicatrices y cambios bruscos de crecimiento, así como las fechas estimadas de establecimiento de los árboles, se han contrastado con datos de fuentes documentales, geomorfológicas, meteorológicas e hidrológicas. Se ha comprobado que, en estas pequeñas y medianas subcuencas, con precipitaciones muy heterogéneas a causa de la orografía, los datos instrumentales (a menudo muy escasos) pueden no reflejar adecuadamente la dinámica hidrológica. Por tanto, se constata que el análisis de las fuentes dendrogeomorfológicas y documentales es fundamental para caracterizar y evaluar la incidencia de estas inundaciones torrenciales en diferentes ámbitos territoriales.

PALABRAS CLAVE: Dinámica Torrencial, Anillos de Árboles, Registros Instrumentales, Datos Históricos, Análisis Geomorfológico, Subcuencas de Romadriu y Flamisell.

1. Introduction

Mountainous areas are prone to torrential floods characterized by their ability to mobilize large volumes of sediment and wood material at a high velocity (Victoriano, *et al*., 2018a and references within). This is the case of the upper catchment of the Noguera Pallaresa River (Lleida, Spain), where the intense rainfall in 1907, 1937, and 1982 triggered extensive flash flooding, causing large morphological changes and major damage (Servei Geològic de Catalunya, 1983; Balasch, *et al*., 2008). Among these, the most recent event occurred after high-intensity storms between November 6th and 8th, 1982, which caused 14 fatalities and considerable financial loss, as well as numerous landslides and debris flow in the Eastern Pyrenees.

Although these cases of extensive flooding are well identified and their main parameters described (e.g. Balasch, *et al*., 2008), the shortage of meteorological and hydrological records, constrains more detailed knowledge of the damaging events. Thus, in order to understand the heterogeneous response of the different mountain subcatchments to these rainfalls, it is necessary to make use of non-systematic data sources, such as botanical, historical, and sedimentological records, as well as different methods to be employed (including Dendrochronology and its application to Dendrogeomorphology). These records and methods have been recognized as important sources of information for providing insights into the variability of floods in space and time (Wilhelm, *et al*., 2019). Particularly, the oscillation of the characteristics of the tree rings over time constitutes one of the main sources of indirect information concerning events of biotic, abiotic, or anthropic nature, including floods (Qie, *et al*., 2022). Its main applications are focused on the dating of past events and the reconstruction of environmental conditions. In the past two decades, the application of Dendrogeomorphology to the analysis of past flooding in Spain has significantly improved the understanding of such events by contributing estimates of the frequency and magnitude of floods in ungauged mountain catchments, thereby reducing uncertainties in the hazard evaluation and during model calibration and validation processes (e.g., Díez-Herrero, *et al*., 2013; Garrote, *et al*., 2018; Bodoque, *et al*., 2020). In addition, relevant information is obtained by the combination of multiple sources, which increases the accuracy and validity of the reconstructions (Williams, *et al*., 2022).

Nevertheless, most of the previous works in the scientific literature are focused on one catchment or a small area. These studies are useful for completing local flood chronologies, but not for understanding the different hydrologic and geomorphic responses of contiguous subbasins to one meteorological extreme event, depending on their land use cover or changes. The inter-comparative studies among different catchments have both, a scientific interest (e.g., controlling factors and geomorphic thresholds; Kondolf & Piegay, 2003) and a technical application to land planning and management.

Thus, to extend the information about the spatial and temporal extension of floods in mountainous areas, where few or no meteorological and hydrological stations are available, this work analyzes two specific rivers in the upper catchment of the Noguera Pallaresa River (Figure 1). The area has been studied before, and information has been obtained from a tributary, the Portainé stream, which in recent decades has been affected by significant torrential flooding (Génova, *et al*., 2018; Victoriano, 2018; Victoriano, *et al*., 2018a, b; Furdada *et al*., 2020). We expand the existing data by studying the Romadriu subcatchment and the Ramiosa and Flamisell streams (Figure 1), which has enabled us to enlarge the spatial scale and compare the hydrologic response contrasting areas in terms of the

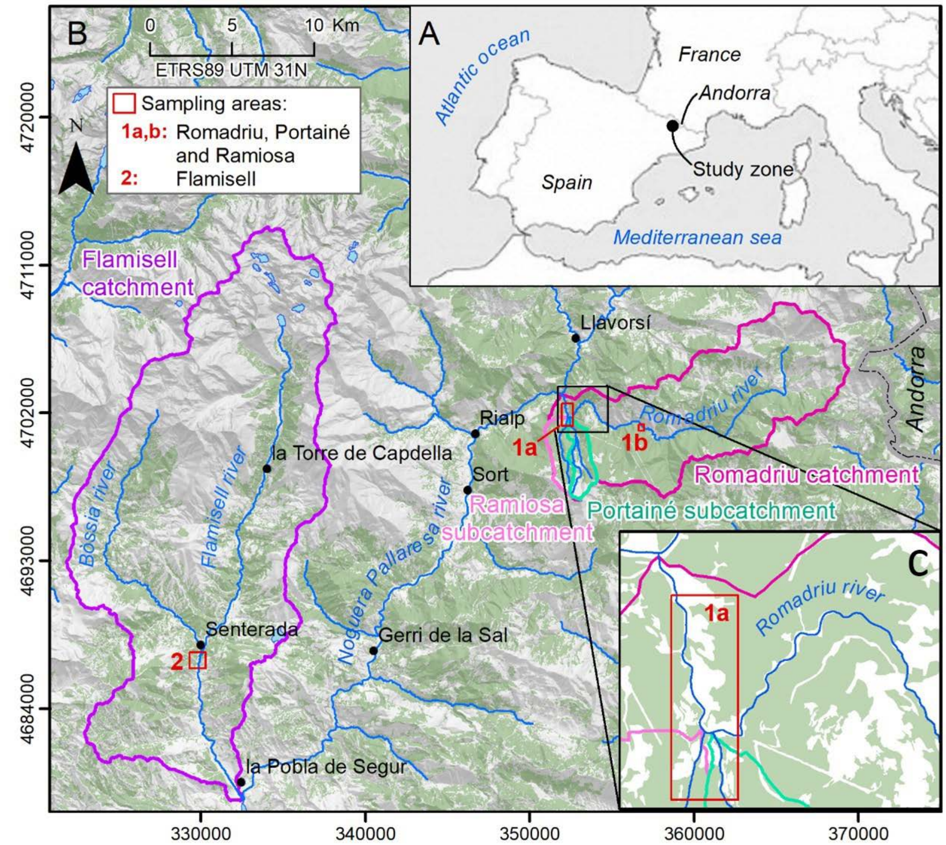

Figure 1. A: Geographic setting of the study area in the Pyrenees; B: Location of the upper Noguera Pallaresa catchment, the Romadriu subcatchment with the Portainé and Ramiosa streams, and the Flamisell subcatchment; C: Detail of the confluence of the Portainé and Ramiosa streams with the Romadriu River. The sampling zones 1a, 1b, and 2 are shown in red. Shadowed relief and forest cover background the property of ICGC (CC by 4.0).

Figura 1. A: Situación geográfica de la zona de estudio en los Pirineos; B: Localización de la cuenca alta del Noguera Pallaresa, la subcuenca del Romadriu con los arroyos Portainé y Ramiosa, y la subcuenca del Flamisell; C: Detalle de la confluencia de los arroyos Portainé y Ramiosa con el río Romadriu. Las zonas de muestreo 1a, 1b y 2 se muestran en rojo. El relieve sombreado y la cubierta forestal son propiedad de ICGC (CC by 4.0).

anthropogenic use of the territory and the geomorphological setting.

Our purpose in this work has been to collect and compare the dendrogeomorphological information provided by the living trees sampled along these streams. We combine their estimated establishment date with evidence of tree damage caused by torrential flooding, mainly scars and abrupt growth changes, to reconstruct the spatial and temporal occurrence of the events. This information is then compared with the available geomorphological, documentary, meteorological, and hydrological data to contribute to the knowledge of the dynamics of these subcatchments.

2. Study area

The Noguera Pallaresa River catchment (Lleida, Spain) has a dominant north-south direction and extends throughout the Pyrenees from the Aran valley to the south, where the river flows to the Camarasa reservoir (pre-Pyrenees), upstream from its confluence with the Segre River. The catchment can be divided into two large sections according to its geographical position, the Alto or Upper part of the Noguera Pallaresa being the northernmost section, which is a generally high mountain area. In the Pyrenees, the Upper Noguera Pallaresa has a catchment area of 1,931 km^2, including the contributions of the main river and various tributaries. Geologically, the Pyrenees consist of an intracontinental Alpine fold and thrust belt resulting from the convergence between the Iberian and European plates from the Late Cretaceous to the Oligocene. The oldest rocks, affected by the previous Variscan orogeny, outcrop in what is known as the Axial Zone and are made up of Paleozoic sedimentary series (sandstones, conglomerates, marbled limestones, and slates) and plutonic rocks (granites); the upper section of the Noguera Pallaresa catchment basically extends over these rocks. Discordantly on these and geographically in more southern areas, Mesozoic and Cenozoic rocks outcrop (conglomerates, sandstones, clays, marls, and limestones), on which the lower section of the catchment is located (Muñoz, 1992).

According to Folch, *et al*. (1984), different types of vegetation exist in the region: Mediterranean and sub-Mediterranean (oak forests of *Quercus ilex* L., *Quercus faginea* Lam. and *Quercus pubescens* Willd.); Central European mid-mountain (pine forests of *Pinus sylvestris* L. and a few beech forests of *Fagus sylvatica* L.), alpine and subalpine mountain (meadows and fir forests of *Abies alba* Miller and pine forests of *Pinus uncinata* Ramond ex DC.), and riparian forests (willow –*Salix* spp.- and alder forests of *Alnus glutinosa* (L.) Gaertn.). At increasing altitudes in the Romadriu subcatchment, *Quercus petraea* (Matt.) Liebl., mixed pine-spruce forest of *P. sylvestris* and *A. alba* Miller are also found, while on the banks of the streams and rivers, there are also ash forests of *Fraxinus excelsior* L. and other mixed deciduous forests with *Tilia platyphyllos* Scop. and *Corylus avellana* L. (Carreras, 1993).

The study area comprises two types of climates: in the northernmost area, Western Pyrenean Mediterranean (annual rainfall 1,000-1,300 mm, and average temperatures 2-9 ºC), and in the southern area Western Pre-Pyrenean Mediterranean (annual rainfall 650-900 mm, with average temperatures of between 9-12ºC) (https://www.meteo.cat/wpweb/climatologia/el-clima/descripcio-general/). In general, the highest values of precipitation are reached in both the right-hand margin areas of the upper Noguera Pallaresa catchment and the upper and middle sections of the Flamisell subcatchment, where winter precipitation at altitude usually occurs in the form of snow. The rainfall events of high intensity in the Romadriu subcatchment occur in spring and summer, mainly as convective storms (https://www.meteo.cat/climatologia/atles_climatic/). The orography controls the generation of convective cells in the upper part of the drainage catchments (Trapero, *et al*., 2013b), which increases precipitation, as at the Portainé summit, and produces very uneven precipitation intensities in weather stations close to each other (Furdada, *et al*., 2020). Torrential events in Portainé, therefore, are mainly related to intense and localized convective summer storms (pers. comm. of different witnesses and https://www.meteo.cat/climatologia/atles_climatic/). On the other hand, in the Flamisell subcatchment, the rainfall regime presents maximum precipitation in autumn and spring (https://www.meteo.cat/wpweb/climatologia/el-clima-ahir/climatologia-comarcal/)

Moreover, regarding the rainfall pattern, according to Furdada, *et al*. (2020) (period 1917-2017) it can be concluded that there is no statistically significant change trend and no increase or decrease in rainfall.

3. Material and methods

3.1. Sampling and dendrochronological analysis of tree-ring growth

Two tributaries of the Upper Noguera Pallaresa are studied: the Romadriu River (in the left-hand margin) and the Flamisell River (in the right-hand margin) (Figure 1 and Table 1). In the Romadriu subcatchment, the Portainé and Ramiosa streams (tributaries of the Romadriu) were sampled between March 2014 and March and September 2015, while between the end of May and the beginning of June 2016, other areas close to the riverbanks of the Romadriu River itself were also sampled. The lower section of the Portainé stream, which forms an elongated cone of alluvial debris at its confluence with the Romadriu, has been intensively studied and the results obtained were published by Génova, *et al*. (2018) and Furdada, *et al*. (2020). The cone is covered by a very diverse hardwood forest, dominated by species such as *Populus tremula* L., *Fraxinus excelsior* L., *Populus nigra* L., *Prunus avium* L. and *Betula pendula* Roth, along with scattered specimens of *Tilia platyphyllos*, *Quercus petraea* (Matt.) Liebl., *Juglans regia* L., *Acer campestre* L., and *Salix caprea* L.). Around the Ramiosa stream, which in the same area flows into the Romadriu River, there is a similar forest, although here *Quercus petraea* and *Fraxinus excelsior* are more frequent. On the other hand, in the sampled areas of the Romadriu riverbank *Populus tremula* and *Populus nigra* dominate. The pre-

Table 1. Morphometric parameters of the subcatchments and streams in the study area (Max. E: Maximum Elevation; Min. E: Minimum Elevation; Vr: Vertical relief; A: Area; RS: River Slope; Mr.: Melton ratio; Or: Main Orientation of the catchment.
Tabla 1. Parámetros morfométricos de las subcuencas y arroyos en el área de estudio (Max. E: altitud máxima; Min. E: altitud mínima; Vr: relieve vertical; A: área; RS: pendiente del río; Mr: razón de Melton; O: orientación principal de la cuenca.

Subcatchment and streams	**Max. E (m a.s.l.)**	**Min. E (m a.s.l.)**	**Vr (m)**	**A (km2)**	**RS (m/m)**	**Mr (km/km)**	**Or**
Romadriu	2789	778	2011	110	0.05	0.19	W
Portainé	2437	950	1487	5.3	0.25	0.64	N
Ramiosa	2389	943	1446	5.3	0.26	0.63	N
Flamisell	2983	501	2482	349	0.09	0.13	S

sence of a ski resort in Portainé from 2006-2008 resulted in the different behavior of flood and debris flow dynamics (Furdada, *et al*., 2020), leading to the sedimentation of the current cone at the confluence of the Portainé stream with the Romadriu River. In the Ramiosa catchment, the channel flow is incised in the bedrock.

In October 2018, a small area of ~500 m2 in the Flamisell subcatchment, was sampled in a dense riparian forest growing on a large gravel bar, consisting mainly of *Alnus glutinosa* (L.) Gaertn., together with scattered *Populus nigra* trees. The area is situated approximately 1 km south of the town of Senterada and downstream of the small dam or weir of Senterada (0.12 Hm3, 26.5 m long and 3.7 m high above the channel, built between 1919 and 1920; Galí, 1922). This sampling area, located immediately downstream of the weir, was chosen because a large number of trees with damage and scars were found, and also to explore the effect of this small hydraulic structure.

The dendrochronological sampling is focused mainly on trees that presented clear signs of damage (Stoffel & Bollschweiler, 2008; Díez-Herrero, *et al*., 2013; Stoffel & Corona, 2014; Génova, *et al*., 2015, 2018), potentially caused by the impact of boulders and sediment particles or floating material carried by the floods (mainly logs or large pieces of wood). The main indicators of macroscopic damage identified consisted of scars, tree crown loss or loss of the main stem, tilting trunks, and dead trees (Figure 2). Other nearby trees were also sampled, because although they did not show any external signs of damage, they may either have been wounded at the base covered by dragged material or perhaps had sustained old internal wounds covered by callus (Génova, *et al*., 2015, 2018).

Additional data were collected for each tree selected, including general dendrometric data (perimeter, height, dominance) and the size of the wounds. Furthermore, sketches of the sampled trees and the environment were made, their precise location was determined with differential GNSS, their detailed geomorphological position (elements or facets; such as river bank, channel bar, floodplain), and photographs were also taken.

The extraction of the dendrochronological samples (cylindrical cores) was carried out using a 400 mm long Pressler borer with an internal diameter of 5 mm (Grissino-Mayer, 2003). At least 2 samples were extracted from each selected specimen representing the trunk growth, one in the flow direction and the other in the opposite direction. Other samples close to the scars or the callus were likewise extracted to complete the information (Stoffel & Bollschweiler, 2008; Génova, *et al*., 2018), both the trunks and replacement branches of decapitated trees (Figure 3). The extracted samples were placed on wooden supports for conservation and drying and, once dry, the usual preparation procedures were followed before measurement. In addition, some wedges with parts of the callus and complete sections of the trunk of dead or badly damaged trees were also obtained (Génova, *et al*., 2018).

We used the LINTAB measurement table with a precision of 0.01 mm and the associated computer program TSAP-Win to measure the tree rings and compile temporal tree-ring growth data series. The tree-ring series were dated by assigning dates to each value of the series using synchronization techniques to perform qualitative and quantitative, visual and statistical analyses (Cook & Kairiukstis, 1990), as well as using the statistical functions (mainly Standard t-value and synchronicity) of TSAP-Win, and results were verified using the software Cofecha (Grissino-Mayer, 2001). First, we synchronized the tree-ring series from each tree, which was then averaged and synchronized with those from the other trees of the same species.

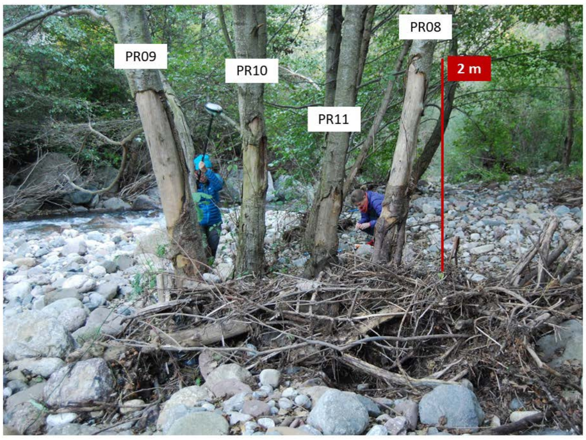

Figure 2. Sampling in the alder forest of the Flamisell River. The trees show scars and peelings caused by floods that reached a maximum height of 2 m. The dragged material can still be seen in the sampling year (2018).
Figura 2. Muestreo en la aliseda del río Flamisell. Los árboles muestran heridas y descortezados provocados por inundaciones que alcanzaron hasta una altura máxima de 2 m. El material arrastrado aún se puede observar en el año de muestreo (2018).

Figure 3. Dendrogeomorphological sampling in 2018 with a Pressler borer on an alder (*Alnus glutinosa*) on the banks of the Flamisell River, close to the scar caused by one flood.
Figura 3. Muestreo dendrogeomorfológico de un aliso (Alnus glutinosa) de la ribera del río Flamisell con barrena de Pressler en 2018 cerca de la herida provocada por una inundación.

3.2. Dendrogeomorphological analysis

We selected and analyzed marks and other evidence in the dated tree-ring series that could provide information on torrential floods (Shroder, 1980; Stoffel and Bollschweiler, 2008; Díez-Herrero, *et al*., 2013; Ruiz-Villanueva, *et al*., 2013; Stoffel & Corona, 2014; Génova, *et al*., 2018), mainly as follows:

- Estimated age of the establishment date of the trees. Plant succession processes occur after destructive events and are recorded by the age of the trees established later. Most of the samples reached the pith and no age adjustments to individual chronologies were considered necessary. However, to roughly estimate the establishment date of each species, 5 years were added to the maximum and average ages to account for the years the trees take to reach the sampling height.
- Presence of external wounds or internal scars characterized by callus or unstructured tissue. This is done by synchronizing and dating the incomplete series obtained in the damaged area with the complete ones from other areas of the tree.
- Abrupt growth changes. The suppression or formation of very narrow rings could be a consequence of wounds or partial trunk burial by deposited sediments, which may also occur when trees are damaged or tilted. A growth release could be the result of reduced competition due to the disappearance of neighbouring trees during floods and/or access to nutrient-rich material and water deposited by flooding.

Abrupt growth changes (suppressions and releases) in tree-ring growth series are responses to different possible inputs. Therefore, they were only taken into account as complementary data when they were correlated with other indications and affected more than 10 % of the trees. These indicators were analyzed using the LRM software (List Ring Measurement; Holmes, 1999), which identifies the significant years in growth change according to their representativeness in groups of trees. In the most recent study carried out in the Flamisell subcatchment, where the trees were young, this analysis was complemented with a study of growth changes according to the proposal put forward by Nowacki & Abrams (1997) and previously used in Dendrogeomorphology (for example in Sorg, *et al*., 2010 and Malik, *et al*., 2021). The percentage change in the growth of each tree from the date of the possible event (GC) was determined using the growth mean of 2 years before (M1) and the growth mean of 2 years after (M2), according to the formula:

$$\%GC=(M2-M1)/M1\cdot 100$$

considering the threshold for recognizing the change in each tree to be ≥25%.

On completion of the analysis of the different marks and signals registered in the tree rings, we follow the proposal by Génova, *et al*., (2018) to date the recognized evidence of damage. The events are therefore dated with a biannual denomination, the dendrogeomorphological year, which indicates that they may have first started at the end of the formation of the previous ring; that is, during the latency period of the trees until the end of the year's growth.

3.3. Documentary, geomorphological and instrumental data

Documentary data on recent floods and human activities were obtained from different technical reports (IGC, 2008; ICGC, 2010a,b, 2011 and 2013a,b; IGC *et al*., 2013). Historical data on the main rainfall and past flooding were obtained from local witnesses, archives (mainly from the Arxiu Comarcal del Pallars Sobirà), newspaper libraries, and the work by Balasch, *et al*. 2008. The PREDIFLOOD (Barriendos, *et al*., 2014) and INUNGAMA flood databases (Llasat, *et al*., 2013), handled and managed by M. Barriendos and C. Llasat (Universitat de Barcelona), respectively, were also consulted. Images provided by the company in charge of the Mal Pas hydroelectric infrastructure (https://ca.wikipedia.org/wiki/Central_hidroel%C3%A8ctrica_de_Mal_Pas) helped us to analyze the dynamics of the torrential flows that affected the Portainé stream in 2008 and 2010 (Garcia-Oteyza, *et al*., 2015; Génova, *et al*., 2018; Victoriano, *et al*., 2018b). The collection of photographs belonging to the La Pobla de Segur Fire station, showing the impacts of the 1982 floods, were used to corroborate the high energy of the event and its destructive capacity.

The detailed geomorphological mapping, together with the positions of the affected trees at the mouth of the Portainé stream to the Noguera Pallaresa River, were presented and analyzed by Victoriano, *et al*., (2018b), who related the different geomorphologic units with the relative position of the damaged trees and the hydraulics of the floods. The results obtained have been completed and compared with those of the Flamisell study area. Vertical aerial photographs and multi-temporal orthophotographs (period 1946-2018) were collected in both the Flamisell and Romadriu study areas. Photointerpretation was carried out to detect changes due to fluvio-torrential dynamics using criteria consisting of tree mass density, coloration, and texture (indicative of sediment transported and deposited shortly before the photograph was taken, etc.). The 1982 vertical aerial photographs, obtained one month after the flood, provide only limited information due to the shadows in the narrower and deeper valleys. Although it was not possible to interpret the entire valley floor of the Romadriu River, the photointerpretation of the shadow-free sections provided relevant information regarding the effects of the flood (see Results section).

Although there are numerous meteorological stations around the Flamisell and the Romadriu subcatchments, none of them are located within the Flamisell area and only those of Salòria and Portainé (in operation since 2011) are situated within the Romadriu subcatchment. Furthermore, many of them have short time series or considerable gaps. Figure 4 shows the stations from which data have been used in this work. Original data have been used (both from https://www.meteo.cat/observacions/xema, with point-selective daily data from June 2009 to the present, and from MeteoPirineu) and data cited in the works by Palau, *et al*., (2017), Trapero, et al., (2013a) and Bech, *et al*., (2011). Palau, *et al*., (2017) take precipitation values from various meteorological stations in a detailed study of the 21/Aug./2015 event. Bech, *et al*., (2011) defined isohyets from real data of 24 h accumulated precipitation in the regional 1-2/Nov./2008 event, while Trapero, *et al*. (2013a) performed simulations of the same event using the data from Bech, *et al*., (2011), considering 24 h of accumulated precipitation. From these two works, we selected the ranges of precipitation registered in the set of stations analyzed. In addition, monthly and annual daily maximum rainfall data have been obtained from the Anuaris de dades meteorològiques (Yearbooks of meteorological data) of the Catalan Meteorological Service (https://www.meteo.cat/wpweb/climatologia/serveis-i-dades-climatiques/anuaris-de-dades-meteorologiques/).

Meteorological data for the Portainé stream have been collected and analyzed by Victoriano, (2018) and Furdada, *et al*. (2020). The most significant data were selected for the present work and are presented in the following sections. Moreover, reports on "Singular weather events" (https://www.meteo.cat/wpweb/climatologia/butlletins-i-episodis-meteorologics/episodis-meteorologics/) were consulted and cross-checked with rainfall and gauging data whenever necessary or possible (due to short series, which do not cover the periods of interest or contain data gaps). For example, for the Flamisell, when no "Singular weather events" were found that could explain the damage to the vegetation (e.g. in the dendrogeomorphological year 2009-10, see section 4.3) the dates of rainfall events of interest (see section 4.3) were explored in the meteorological yearbooks. For these dates, using the Automatic Stations Map, the precipitation in each one of the stations was selected and compared. It should be noted that the significant rainfall events addressed by Bech, *et al*., (2011) and Trapero, et al., (2013a), and also described in the "Singular weather events", are indeed well known, but their hydrological and derived geomorphological effects have not been studied before.

There are no gauging stations in the Romadriu subcatchment, so there are no discharge data for this subcatch-

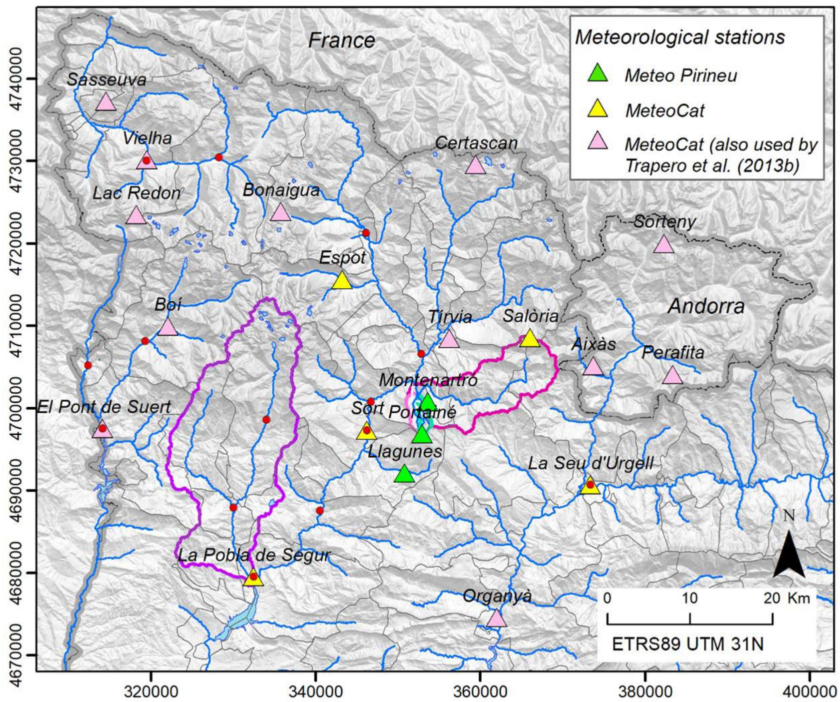

Figure 4. Meteorological stations used in this study (Tables 5 and 6). Green and yellow indicate the stations from which data have been obtained directly and the Portainé station, with data cited in Palau et al. (2017). In pink, the stations located in the study area used by Trapero et al. (2013a) to calibrate their simulations of the extraordinary meteorological events, considering the orography, of 1-2/Nov./2008. The hydrographic network, studied subcatchments and towns correspond to those of Figure 1.

Figura 4. Estaciones meteorológicas utilizadas en este estudio (Tablas 5 y 6). Los colores verde y amarillo indican las estaciones de las que se han obtenido datos directamente y la estación Portainé, con datos citados en Palau et al. (2017). En color rosa, las estaciones ubicadas en la zona de estudio utilizadas por Trapero et al. (2013a) para calibrar sus simulaciones de los eventos meteorológicos extraordinarios considerando la orografía del 1-2/Nov./2008. La red hidrográfica, las subcuencas estudiadas y las poblaciones se corresponden a los de la Figura 1.

ment. In the Flamisell subcatchment, there are 3 gauging stations (Table 2).

We use data from station 9267 – Capdella (in operation since 1989) - as it provides the longest discharge series and is the station that contains the periods of the establishment of the riparian trees and the dendrogeomorphological years with detected damage on these trees (see Results section), as well as being relatively close to the sampling area (~18 km upstream). For this station, data are available on daily average discharges and monthly maximum instantaneous discharges (m^3/s). Although no data exist for the following periods: 26/Nov./1990 – 18/Jan./1991; 19/Jul./2000 – 19/Aug./2000; 31/Jul/2002 – 05/Sep./2002; 01/Oct./2006 – 30/Sep./2007; 01/Oct./2008 – 28/Mar./2011 and while these data do not reflect the total daily discharges, they nevertheless indicate the days on which significant flooding occurred.

At station 9181 - La Pobla de Segur (in operation from 1965 to 1991) - approx. 9 km below the sampling area, at the confluence with the Noguera Pallaresa, there are no data from 01/Nov./1982 to 01/Oct./1983 due to the destruction of the gauging station caused by the November 1982 flood. The series ends when the period of establishment of riparian trees begins, so no useful data was available for interpreting the damage to the vegetation. In any case, the data of the monthly contributions in hm^3 of the Flamisell were retrieved to obtain an order of magnitude of the contributions of this subcatchment. These data were compared with the 1982 Flamisell flood discharge reconstruction obtained by Balasch, *et al*., (2008). The 9274 – Sallente P.P. station - provided no useful data for the present work.

All the data obtained, both documentary and geomorphological, were unfortunately incomplete, and the rainfall and discharge data series have gaps or are short. Faced with these limitations, the methodology used is based on the compilation and chronological ordering of each type of data and, subsequently, on their comparison and joint analysis. Geomorphological and forest density changes in the sampled areas were analyzed from the middle of the 20th century to the beginning of the 21st using aerial photographs and orthophotos from different periods. They were then compared with documentary data on floods (using historical and testimonial data and photographs of the events) and cross-checked with the dendrogeomorphological years with the detected damage to trees. The few available instrumental series (meteorological and hydrological) were also compared to the establishment of the riparian forest, the documented torrential flood events, and the dated damage to the trees. All these analyses contribute to the understanding of the dynamics of subcatchments of different dimensions facing floods of different magnitudes. As Kondolf & Piegay (2003) suggest, working with the convergence of evidence between the various data sources and comparing multiple zones increases knowledge and takes the complexity of the systems into account. In our work, the areas under study consist of different spatial scales, have undergone their own geomorphological and vegetation colonization evolution, and present a particular response to torrential flooding.

4. Results

4.1. Riparian forest characteristics: tree species, sizes, and ages

110 trees of 11 different species (*Acer campestre*, *Alnus glutinosa*, *Fraxinus excelsior*, *Juglans regia*, *Pinus sylvestris*, *Populus nigra*, *Populus tremula*, *Prunus avium*, *Quercus petraea*, *Salix caprea*, and *Tilia platyphyllos*) are analyzed, including; a) 81 trees in the Romadriu subcatchment (9 trees in the Ramiosa stream, 15 trees in the Romadriu river, and the 57 trees in the Portainé stream already studied in our previous work; and b) 29 trees in the Flamisell subcatchment. Almost all of them are angiosperms belonging to very different families and with different types of xylem, from ring pore (e.g.: *Quercus petraea*, *Fraxinus excelsior*) to diffuse pore (e.g.: *Alnus glutinosa*, *Tilia platyphyllos*) or with intermediate characteristics (e.g.: *Populus spp*., *Prunus avium*). Among the sampled species, in which 4 or more

Table 2. Gauging stations located in the Flamisell stream, ordered from upstream to the mouth (Source: Anuario de Aforos2018-2019 «© Ministry for the Ecological Transition and the Demographic Challenge», update: December 2021). XUTM and YUTM correspond to the station coordinates referenced in Datum ETRS89, UTM 31N.

Tabla 2. Estaciones de aforo situadas en el arroyo Flamisell, ordenadas desde aguas arriba hasta la desembocadura (Fuente: Anuario de Aforos 2018-2019 «© Ministerio para la Transición Ecológica y el Reto Demográfico», actualización: diciembre 2021). XUTM y YUTM corresponden a las coordenadas de la estación referenciadas en el Datum ETRS89, UTM 31N.

Gauging stations	Location	Initial year	Final year	Altitude (m a.s.l.)	XUTM	YUTM	Drained area (km^2)
9274	Sallente P.P.	1995	1999	1593	334931	4703907	29
9267	Capdella	1989	2018	1268	334931	4703907	74
9181	La Pobla de Segur	1965	1991	525	332138	4679330	342

trees are analyzed (Table 3), poplars (*Populus nigra*) and oaks (*Quercus petraea*) stand out as the thickest. It should be noted that, since the oaks have a slightly lower average perimeter, they can reach twice the age of the poplars. Quaking aspen (Populus tremula) almost doubled the perimeter and the tree-ring width mean of the common ash (Fraxinus excelsior), despite having the same estimated mean age, while the alders studied (Alnus glutinosa), which present perimeters similar to common ash, rarely exceeded twenty years of age (Table 3).

In the Flamisell subcatchment, both poplars and alders have the greatest average ring width (although the fact that these are comparatively younger trees must be taken into account), while in the Romadriu subcatchment, the poplar is also the species with the largest tree-ring width average.

Large differences are identified between the average and maximum ages obtained in the Romadriu subcatchment, compared to those obtained in the Flamisell (Table 3), and therefore also in terms of the dates of forest establishment. In the Romadriu, most of the trees belonging to the most predominant species (*Populus tremula*, *Fraxinus excelsior*, *Populus nigra*) that comprise the riparian forest were established in the 1950s or thereafter. Other trees were older, establishing themselves between the early 20th century and the 1920s: oak (*Quercus petraea*), lime (*Tilia platyphyllos*), and walnut (*Juglans regia*); while only a few others, such as cherry trees (*Prunus avium*), were much younger. In contrast, the alders and poplars on the Flamisell riverbanks were much more recent, their establishment being estimated as in the 1990s.

4.2. Temporal and spatial evidence of flooding

4.1.1. Dating the tree damage

Table 4 shows the main evidence of damage recorded (scars and growth suppression) in the two subcatchments under study, and the dendrogeomorphological year in which it was estimated that this damage occurred. For the Romadriu subcatchment, we have selected data since 1960 from our previous work in the Portainé stream (Génova, *et al*., 2018) and we have added the damage detected in the Ramiosa stream and other sampled areas of the Romadriu River.

In the Flamisell subcatchment, the dates of the damage are very recent because it is a young forest, and thus, the greatest tree growth suppressions occurred in 2008, 2010, and 2015 (Figure 5). We may therefore highlight the number and percentage of external injuries dated in the period 2014-15 (72 % of the trees, Table 4), while the dendrogeomorphological years 2007-08 and 2014-15 are those that present a greater negative percentage change in

Table 3. Characteristics of the species with 4 or more individuals analyzed in the Romadriu and Flamisell subcatchments. a: age in 2015, b: age in 2018. Sp: Species, N: Number of trees, Mp: Mean perimeter, SD: Standard Deviation, Mrw: Mean ring-width, Ma: Mean age, Mxa: Maximum age, Ee: Oldest Estimated date of establishment. Ag (*Alnus glutinosa*), Fe (*Fraxinus excelsior*), Jr (*Juglans regia*), Pa (*Prunus avium*), Pn (*Populus nigra*), Pt (*Populus tremula*), Qp (*Quercus petraea*), Tp (*Tilia platyphyllos*).
Tabla 3. Características de las especies con 4 o más individuos analizados en las subcuencas de Romadriu y Flamisell. a: Edad en 2015, b: edad en 2018. Sp: Especie, N: Número de árboles, Mp: Perímetro medio, SD: Desviación estándar, Mrw: Anchura media de anillo, Ma: Edad media, Mxa: Edad máxima, Ee: Fecha estimada de establecimiento más antigua. Ag (*Alnus glutinosa*), Fe (*Fraxinus excelsior*), Jr (*Juglans regia*), Pa (*Prunus avium*), Pn (*Populus nigra*), Pt (*Populus tremula*), Qp (*Quercus petraea*), Tp (*Tilia platyphyllos*).

Romadriu subcatchment a						
Sp	N	Mp (cm) ± SD	Mrw (mm) ± SD	Ma	Mxa	Ee
Fe	13	62 ± 17	1.6 ± 0.7	51	60	1950-1959
Jr	4	113 ± 32	2.6 ± 1.1	62	86	1924-1973
Pa	5	61 ± 30	1.9 ± 1.2	43	48	1962-1968
Pn	23	161 ± 56	5.1 ± 2.2	45	56	1954-1978
Pt	21	114 ± 27	2.9 ± 0.8	50	59	1951-1959
Qp	7	134 ± 56	2.1 ± 0.5	82	109	1901-1946
Tp	5	84 ± 29	2.0 ± 0.8	62	81	1929-1948
Flamisell subcatchment b						
Sp	N	Mp (cm) ± SD	Mrw (mm) ± SD	Ma	Mxa	Ee
Ag	23	65 ± 15	5.8 ± 1.4	16	21	1992-1997
Pn	6	65 ± 5.6	6.0 ± 1.2	14	17	1996-1999

Table 4. Scars and suppressions detected and dated in the subcatchments studied. N: Number of trees with evidence, P: Percentage of trees about the total sampled on each subcatchment (only indicated if ≥1%), DGY: Dendrogeomorphological Year.
Tabla 4. Cicatrices y supresiones detectadas y fechadas en las subcuencas estudiadas. N: Número de árboles con evidencias, P: Porcentaje de árboles en relación al total muestreado (sólo se indica si ≥1%), DGY: Año dendrogeomorfológico.

Romadriu Subcatchment					Flamisell Subcatchment				
Scars		Suppressions		DGY	Scars		Suppressions		DGY
N	P	N	P		N	P	N	P	
1	--	9	8%	1973-74	5	17%	19	66%	2007-08
3	3%-	7	6%	1976-77	3	10%	19	66%	2009-10
1	--	9	8%	1987-88	2	7%	17	59%	2011-12
3	3%-	28	25%	1992-93	21	72%	18	62%	2014-15
8	7%	34	31%	1997-98					
4	4%	16	15%	1999-00					
2	2%	27	25%	2005-06					
20	18%	13	12%	2007-08					
6	5%	28	25%	2009-10					

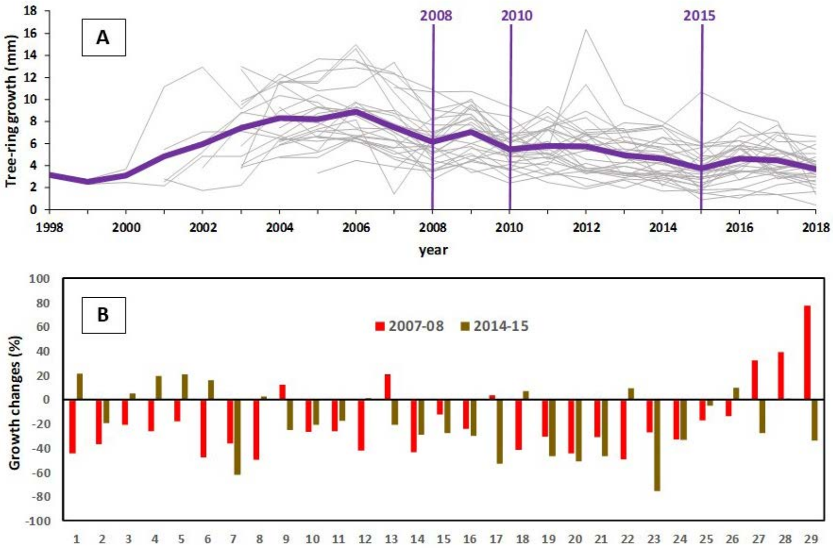

Figure 5. A) Individual tree-ring width series and the average of the trees sampled in the Flamisell subcatchment, indicating the years in which the greatest tree growth suppression occurred. B) Growth changes detected in each sampled tree for the dendrogeomorphological years 2007-08 and 2014-15.
Figura 5. A) Series individuales y promedio de anchura de anillos de los árboles muestreados en la subcuenca del Flamisell, indicando los años en los que se produjo la mayor supresión del crecimiento de los árboles. B) Cambios de crecimiento detectados en cada árbol muestreado para los años dendrogeomorfológicos 2007-08 y 2014-15.

the mean tree-ring widths, 59 % and 45 %, respectively (Figure 5).

4.1.2. Geomorphological and landscape changes

The colonization of the forest in the Portainé stream (Romadriu subcatchment), obtained by analyzing orthophotos, was presented in Génova, *et al*. (2018). Since 1956, when only a few stands of trees were observed, there has been a progressive establishment and development of the forest, both in the cone (riparian forest) and on the surrounding slopes (oak grove). As of 1982, in Portainé and Ramiosa (see the following paragraph), and especially since 1990 in Romadriu as well (Génova, *et al*., 2018), a dense forest mass may already be observed, although the most recent orthophotos indicate that it has also been affected in the Portainé stream due to the last floods and debris flows.

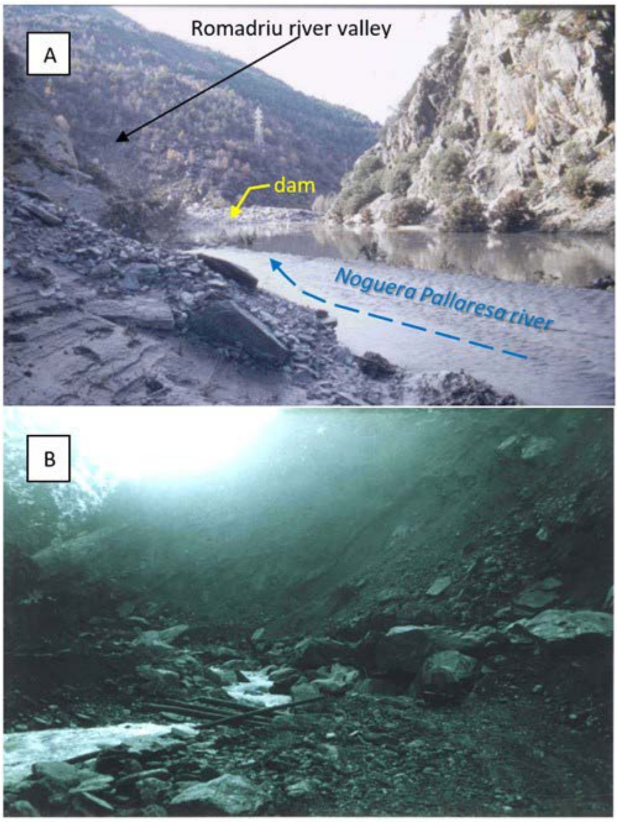

Figure 6. Historical photographs of the effects of the 1982 flood in the Romadriu Valley. A) The dam at the confluence of the Romadriu River with the Noguera Pallaresa River, seen from upstream of the Noguera Pallaresa. B) The mouth of the Romadriu River seen from the Noguera Pallaresa River, completely devastated. Source: Arxiu Comarcal del Pallars Sobirà.
Figura 6. Fotografías históricas de los efectos de la inundación de 1982 en el Valle de Romadriu; A) La presa en la confluencia del río Romadriu con el río Noguera Pallaresa, vista desde aguas arriba del Noguera Pallaresa. B) La desembocadura del río Romadriu vista desde el río Noguera Pallaresa completamente devastada. Fuente: Arxiu Comarcal del Pallars Sobirà.

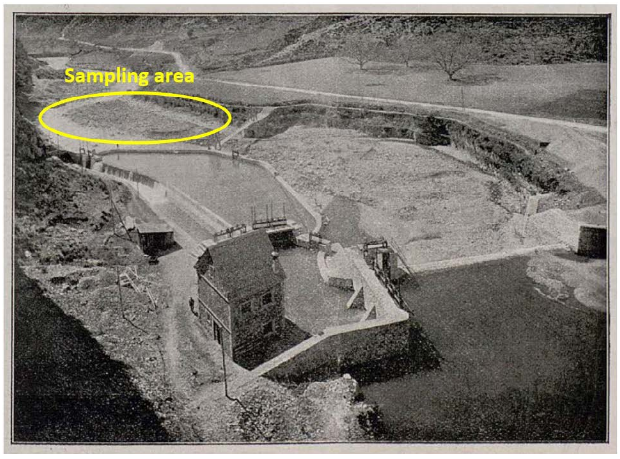

Figure 7. Sampling area on the banks of the Flamisell River indicated in a photograph published in 1922, after the construction of the Senterada-La Pobla de Segur complex (1919-1920). The total absence of riparian vegetation is observed after the construction of the infrastructure (Source: Galí, 1922).
Figura 7. Área de muestreo en la ribera del río Flamisell indicada en una fotografía publicada en 1922 tras la construcción del complejo Senterada-La Pobla de Segur (1919-1920). Se observa la ausencia total de vegetación de ribera tras la construcción de esta infraestructura (Fuente: Galí, 1922).

Despite the shadows that exist in many sectors, the post-flood aerial photographs of December 1982 show that the Romadriu channel was significantly affected, since a large amount of sediment was eroded and transported along the channel, leading to damming at the confluence with the Noguera Pallaresa, where the riparian forest was destroyed (Figure 6). On the other hand, no alterations of the forest mass were observed at the mouths of the Portainé and Ramiosa streams. It should be borne in mind that the small Mal Pas gravity dam, located just upstream from the confluence of the Portainé stream, was built between 1995 and 1997 (as were all the hydroelectric infrastructures built in the Romadriu valley), so they were not affected during this torrential flood.

Regarding the colonization in the Flamisell River corridor, the photograph in Figure 7 shows that the sampling area was completely devoid of vegetation in 1922 when the construction of the hydroelectric infrastructure was completed (1919-1920).

The orthophotos (Figure 8) show that there were very few trees in 1956, while in 1982 (image obtained one month after the flood) the flood had affected the entire channel as well as the adjacent plain, and had deposited sediment (in gray) where the trees sampled would later establish themselves. The historical photographs in Figure 9 show the effects of the flood in Senterada and illustrate its great destructive power. During this event, the Flamisell contributed 16,4 hm^3, which is ~25 % of the total annual discharge of the Noguera Pallaresa at La Pobla de Segur. The convergence of these data explains how the complete destruction of riparian forest occurred. Subsequently, in 1988 (Figure 8), a possible beginning of tree colonization can be observed (it is the closest image in time to the establishment of most of the sampled trees). In the images corresponding to the years 2012, 2014, and 2017, the floods detected by the dendrogeomorphological analysis show no evidence of having affected the development of the forest mass. The same occurred with the flood of June 2008 (Figure 10), unknown until this work and for which no rainfall data is available, and which may well have been detected by wounds and other damage to the trees.

4.3. Comparison with instrumental records

Three tables summarizing significant meteorological data selected from different sources and with different

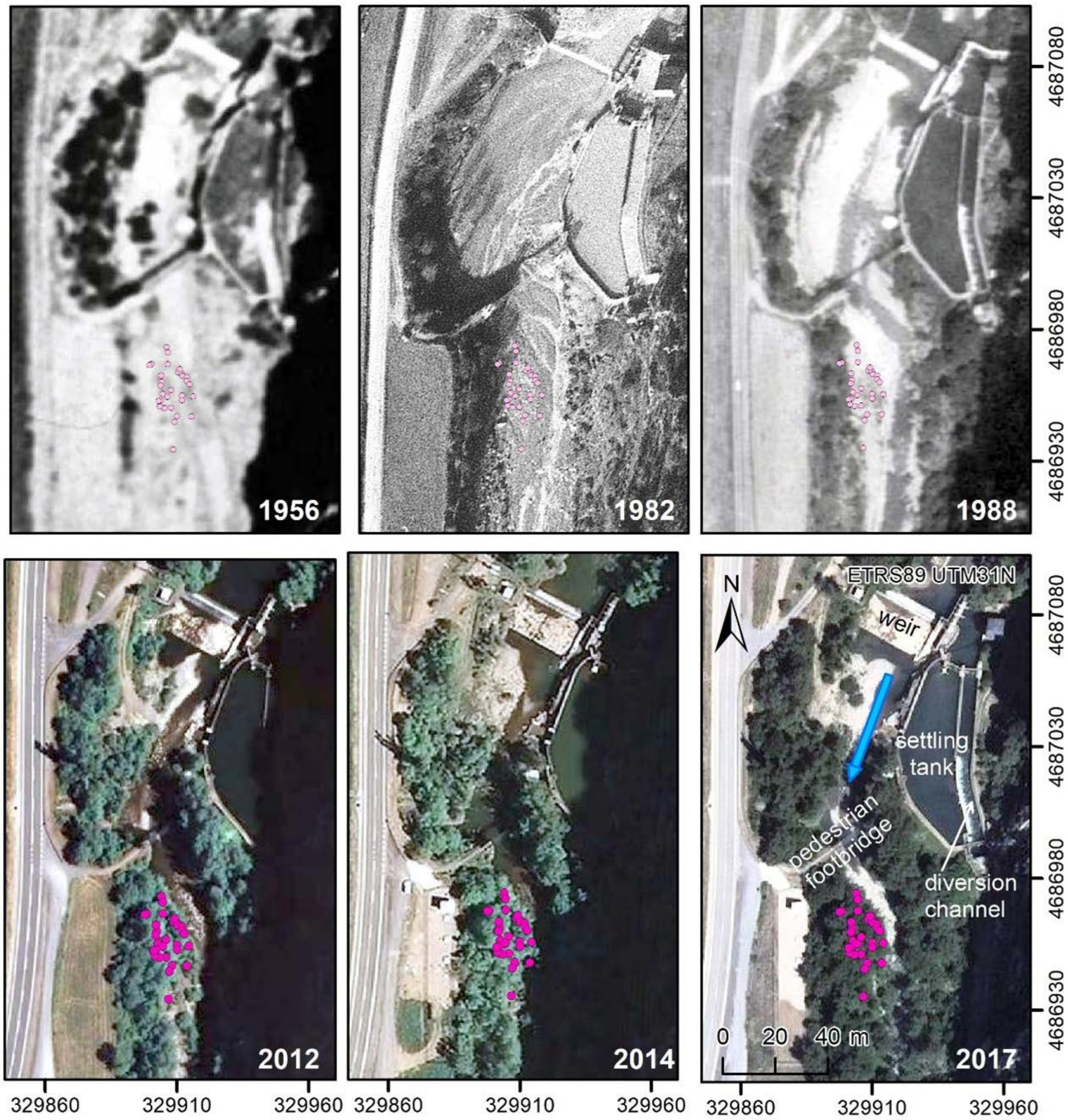

Figure 8. Orthoimages of the Flamisell River sampling area. The weir and the settling tank for the water intake (for hydroelectric exploitation) can be seen at the north and northeast; in the center, the pedestrian footbridge that connects the path with the settling tank. In fuchsia circles: position of the sampled trees; in pale pink circles: their position before their establishment (Orthoimages property of Institut Cartografic i Geologic de Catalunya; CC by 4.0).

Figura 8. Ortoimágenes de la zona de muestreo del río Flamisell. Al norte y noreste se observa el azud y el tanque de sedimentación para la toma de agua (para aprovechamiento hidroeléctrico); en el centro, la pasarela peatonal que conecta el camino con el decantador. En círculos fucsias: posición de los árboles muestreados; en círculos rosa pálido: su posición antes de su establecimiento (Ortoimágenes propiedad del Institut Cartografic i Geologic de Catalunya; CC by 4.0).

criteria are presented below. Tables 5 and 6 present selected meteorological data recorded in the dendrochronological years 2007-08 and 2009-10 (when there was damage to the vegetation in both Romadriu and Flamisell subcatchments), and in the dendrochronological year 2014- 2015 (when damage to the vegetation of the Flamisell subcatchment was verified). The data correspond to the dates of rainfall events of interest, both because of the damage caused to the vegetation (known from technical reports), and because these events are considered significant on a regional scale as well as in the "Singular weather events" of METEOCAT, and consequently may have caused damage to the vegetation.

Table 5 includes selected rainfall data and its classification as local or regional events of the rainfall events of interest described above. Table 6 presents the rainfall comparison of the events of interest described

Figure 9. Photographs of the effects of the 1982 flood in Senterada, approximately 1 km upstream from the Senterada weir and the Flamisell River sampling area. The photographs illustrate the energy of the event and its destructive power. Source: collection of photographs of the impacts of the 1982 flood, Firemen of La Pobla de Segur.

Figura 9. Fotografías de los efectos de la inundación de 1982 en Senterada, aproximadamente 1 km aguas arriba del vertedero de Senterada y del área de muestreo del río Flamisell. Las fotografías ilustran la energía del evento y su poder destructivo. Fuente: recopilación de fotografías de los impactos de la riada de 1982, Bomberos de La Pobla de Segur.

Figure 10. Photographs of the June 2008 flood in the Senterada weir, which affected the sampling area. A: View of the weir from downstream; B: View of the weir from upstream; C and D: View of the trees in the sampling area closest to the channel (Source: Maite Arilla).

Figura 10. Fotografías de la inundación de junio de 2008 en el azud de Senterada, que afectó al área de muestreo. A: Vista del azud desde aguas abajo; B: Vista del azud desde aguas arriba; C y D: Vista de los árboles de la zona de muestreo más cercana al canal (Fuente: Maite Arilla).

above with the monthly and annual rainfall maximums of the network (Figure 4); it specifically shows: a) the maximum monthly rainfall in 24 h in the months of the dates of rainfall events of interest defined above; b) the maximum precipitation in 24 h of the year, indicating the month and day of occurrence; and c) the total accumulated precipitation in each one of the selected rainfall events. When the month in which the maximum precipitation in 24 h occurs coincides (or fails to coincide) with the dates of the rainfall events of interest, it is highlighted in dark blue or light blue, respectively.

Tables 5 and 6 highlight the large variability of rainfall in the different stations for each episode. Table 6 shows that only in the regional episode of November 1st and 2nd, 2008, was the maximum annual 24 h precipitation recorded at all stations (except Sort, where there was no record). Considerable variability is found in the other two regional events since while some stations register their maximum annual rainfall, others do not even register a monthly maximum. It is also evident that, in the four local events, half of the stations did not even register a maximum monthly precipitation in 24 h. This underlines the large variability of precipitation in these mountainous areas.

Table 7 presents the accumulated rainfall at Meteocat stations for three selected dates in 2010, when no “Singular weather events” were found that could explain the damage to the Flamisell vegetation in this dendrogeomorphological year. As explained in the methodology section, the days on which monthly maximum precipitation occurred in each of the weather stations in Table 6 were explored in the meteorological yearbooks and the precipitation in each of the stations presented in Table 7 was obtained from the Automatic Stations Map. This allowed us to discard the rainfall event of 02/Nov./2010 and to consider 09/June/2010 as the one that most likely caused the flood and the damage.

The existing discharge data (average daily discharge and maximum instantaneous monthly discharge peaks) at gauging station 9267-Capdella (Flamisell subcatchment) are presented below. Figure 11 shows the comparison of these data with the establishment riparian forest period and with the years of damage to trees, and the dates of some notable peak flows were highlighted. There is no clear, univocal relationship among the peak discharges or some of the notable historical flows and the damage caused.

The monthly contributions in hm^3 of the Flamisell at station 9181 - La Pobla de Segur (1965-1991) were obtained (Table 8). The contribution of the 1982 flood (16.4 hm^3) was greater than the average monthly contribution, reinforcing the evidence of the great destructive power of this flood. On the other hand, as mentioned before, the weir of Senterada has a capacity of 0,12 hm^3, which corresponds to a storage capacity of barely 0.24% of the maximum monthly contribution and is less than the minimum monthly contribution.

Table 5. Selected rainfall data and its classification as local or regional events; AE: Extension of the event; L: Local; R: Regional. The selected data were recorded in the dendrochronological years 2007-08 and 2009-10 (when there was damage to the vegetation of both subcatchments -Romadriu and Flamisell-) and in the dendrochronological year 2014-2015 (when there was damage to the vegetation of the Flamisell subcatchment). The data correspond to the dates of the rainfall events of interest, both because the damages occurred (known from documentary data), and because they were significant on a regional scale. The data come from both meteorological stations and the works of: i) Bech, *et al*., (2011); ii) Trapero, *et al*., (2013a); iii) Palau, *et al*., (2017); and iv) extracted from the reports of "Singular weather events" (https://www.meteo.cat/observacions/xema). From each source data were extracted: precipitation ranges of the stations used in the works (in italics; Bech, *et al*., 2011 and Traperom *et al*., 2013a); rainfall in specific stations (Meteocat, MeteoPirineu and Palau, *et al*., 2017).

Tabla 5. Datos de lluvia seleccionados y su clasificación como eventos locales o regionales; AE: Extensión del evento; L: Local; R: Regional. Los datos seleccionados se registraron en los años dendrocronológicos 2007-08 y 2009-10 (cuando hubo daños en la vegetación de las subcuencas de Romadriu y Flamisell), y en el año dendrocronológico 2014-2015 (cuando hubo daños en la vegetación de la subcuenca Flamisell). Los datos corresponden a las fechas de los eventos pluviométricos de interés, tanto porque produjeron daños (conocidos por datos documentales), como porque fueron significativos a escala regional. Los datos provienen tanto de estaciones meteorológicas como de los trabajos de: i) Bech et al. (2011); ii) Trapero et al. (2013a); iii) Palau et al. (2017); y iv) extraídos de los informes de "Eventos meteorológicos singulares" https://www.meteo.cat/observacions/xema. *De cada fuente se extrajeron datos: rangos de precipitación de las estaciones utilizadas en las obras (en cursiva; Bech et al., 2011 y Trapero et al., 2013a); precipitaciones en estaciones concretas (Meteocat, MeteoPirineu y Palau et al., 2017).*

Date of the event	FLAMISELL	FLAMISELL (F)/ BOTH SUBCATCHMENTS (BB)	ROMADRIU								AE
	Trapero et al. (2013a) Accum. prec. 24h (mm)	Meteocat: "Events of singular weather" (afectan áreas extensas)	Meteocat Accum. prec. in the event		MeteoPirineu Accum. prec. in the event		Bech et al. (2011) Accum. pr. 24h (mm)	Trapero et al. (2013a) Accum. pr. 24h (mm)	Palau et al. (2017) Intense precipitation 2h duration		
			Station	Precip. (mm)	Station	Precip. (mm)			Station	Precip. (mm)	
12/09/2008	-	-	Saloria: Sort:	43 17.6	-		-	-	-		L
1-2/11/2008	*Range: 60-107.2*	-	Saloria:	113	Llagunes:	113.5	*Range: 60-90*	*Range: 70-90*	-		R
22-23/07/2010	-	-	Saloria: Sort: La Seu:	31.7 73.8 32.4	Llagunes: Montenartró:	34.4 52.2	-	-	-		L
12/08/2010	-	-	Saloria: Sort:	2.4 46.3	Llagunes: Montenartró:	21.4 28.8	-	-	-		L
27/11-1/12/2014	-	**BB**: Snow level oscillating 2000-2500 m. 11 cm (Bonaigua) < New snow accum. precipitation < 70 cm (Boí): 40 mm < episode accum. precip. < 150 mm	-		-		-	-	-		R
20-25/03/2015	-	**F:** episode accum. precip. > 50mm in headwaters and > 40mm in all catchment	-		-		-	-	-		R
21/08/2015	-	-	-		-				Portainé: Sort: La Seu:	30 0.2 0.1	L

Table 6. Rainfall data obtained from meteorological yearbooks (Meteocat [on line3]) and from the different stations (https://www.meteo.cat/climatologia/atles_climatic/). 2nd column: Bech, *et al*., (2011)= (B11), Trapero, *et al*., (2013a)= (T13), Singular Weather Episode (https://www.meteo.cat/observacions/xema)= (ETS). Precipitation: Upper row: maximum monthly precipitation in 24 h of the months of the events in columns 1 and 2 and its date, and (-) if there is no coincidence between the date of the maximum monthly rainfall and the date of the event; middle row: maximum annual rainfall in 24 h and its date; lower row: total rainfall accumulated in each episode. AE: Scope of the episode; L: Local; R: Regional. sd: no data. In bold: if the rainfall coincides with the dates in columns 1 or 2; In dark blue: the maximum monthly precipitation in 24 h coincides with the yearly maximum and the event that causes or could cause damage; In light blue: the maximum annual precipitation in 24 h does not coincide with the event that causes or could have caused damage.

*Tabla 6. Datos de precipitaciones obtenidos de los anuarios meteorológicos (Meteocat [en línea 3]) y de las diferentes estaciones (*https://www.meteo.cat/climatologia/atles_climatic/*). 2ª columna: Bech et al. (2011)=(B11), Trapero et al. (2013a)=(T13), Eventos meteorológicos singulares (*https://www.meteo.cat/observacions/xema*)=(ETS). Precipitación: Fila superior: precipitación máxima mensual en 24h de los meses de los eventos en las columnas 1 y 2 y su fecha, y (-) si no hay coincidencia entre la fecha de máxima precipitación mensual y la fecha del evento; fila central: precipitación máxima anual en 24h y su fecha; fila inferior: precipitación total acumulada en cada episodio. AE: Extensión del episodio; L: Local; R: Regional. SD: sin datos. En negrita: si las precipitaciones coinciden con las fechas de las columnas 1 o 2; En azul oscuro: la precipitación máxima mensual en 24 horas coincide con la máxima anual y el evento que causa o podría causar daño; En celeste: la precipitación máxima mensual en 24 horas del año no coincide con el evento que causa o podría causar daño.*

Date of known events (do-cum. data)	Dates with relevant re-gional rains (according to B11; T13; ETS)	Affec-ted sub-catch-ments	AE	Stations Maximum monthly precipitation in 24h (Meteocat [online3]) of the months of the events in columns 1 and 2. Maximum annual precipitation in 24 hours (Meteocat [online3]) and date on which it occurred. Total accumulated precipitation in the episode (Meteocat [online2])													
				La Seu d'Ur-gell		Salòria		Sort		Espot		Boí		El Pont de Suert		La Pobla de Segur	
				Prec. (mm)	Date	Prec. (mm)	Date	Prec. (mm)	Date	Prec. (mm)	Date	Prec. (mm)	Date	Prec. (mm)	Date	Prec. (mm)	Date
12/09/2008		Romadriu (Portainé)	L	- 54.4 sd	02/11	- 65.9 sd	02/11	sd		- 106.3 sd	02/11	- 107.2 sd	02/11	- 67.4 sd	02/11	- 36.0 sd	02/11
1-2/11/2008	1-2/11/2008 (B11; T13)	Romadriu Flamisell	R	54.4 54.4 sd	02/11 02/11	65.9 65.9 sd	02/11 02/11	sd		106.3 106.3 sd	02/11 02/11	107.2 107.2 sd	02/11 02/11	67.4 67.4 sd	02/11 02/11	36.0 36.0 sd	02/11 02/11
22-23/07/2010		Romadriu (Portainé)	L	19.5 54.6 36.3	22/07 10/10	- 74.7 31.7	10/10	45.8 56.3 73.8	22/07 09/06	37.4 95.1 49.4	22/07 09/06	34.5 60.0 40.7	22/07 09/06	53.9 53.9 59.7	22/07 22/07	- 49.9 5	02/09
12/08/2010		Romadriu (Portainé)	L	- 54.6 8.8	10/10	- 74.7 2.4	10/10	46.3 56.3 46.3	12/08 09/06	- 95.1 5.7	09/06	5.6 60.0 5.6	12/08 09/06	- 53.9 11.5	22/07	- 49.9 20.2	02/09
	27/11-01/12/2014 (ETS)	Flamisell	R	- 41.7 40.9	19/01	60.7 62.5 117.4	28/11 12/10	- 60.9 37.8	20/08	76.8 76.8 150.2	28/11 28/11	67.4 90.7 148.3	28/11 20/08	35.9 57.7 86.9	28/11 20/08	- 54.4 35.3	22/08
	20-25/03/2015 (ETS)	Flamisell	R	11.9 64.1 15.5	22/03 02/11	32.4 84.2 51.1	22/03 02/11	15.0 55.5 22.2	22/03 02/11	26.3 80.3 61.4	22/03 02/11	45.3 45.3 98.6	22/03 22/03	15.2 64.1 35.8	24/03 09/06	19.8 41.7 34.9	24/03 31/07
21/08/2015		Romadriu (Portainé)	L	- 64.1 0.1	02/11	- 84.2 0	02/11	- 55.5 0.2	02/11	- 80.3 3	02/11	- 45.3 1.2	22/03	- 64.1 0.6	09/06	- 41.7 0	31/07

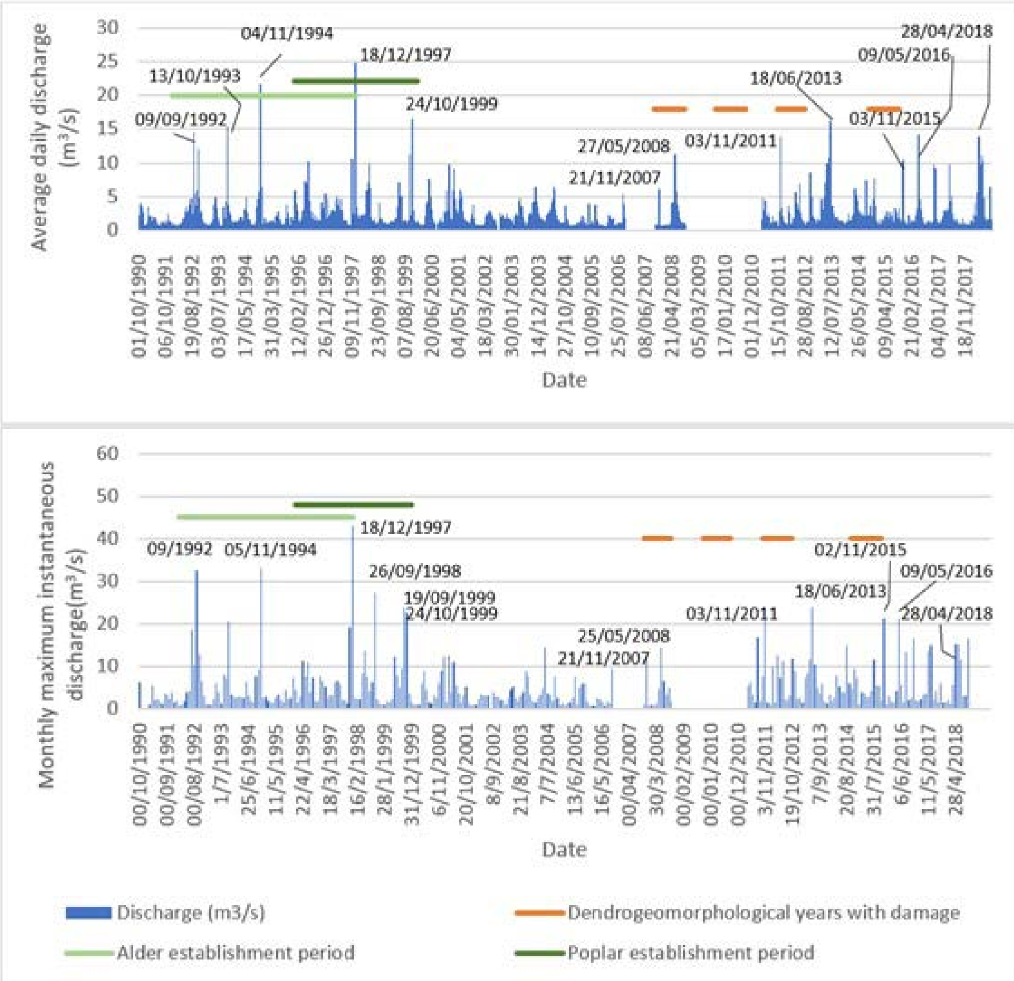

Figure 11. Comparison of the average daily flow and the monthly maximum instantaneous flow at the 9267-Capdella gauging station (Source: Anuario de Aforos 2018-2019 «© Ministry for the Ecological Transition and the Demographic Challenge», update: December 2021) with the estimated periods of tree establishment (alders - *Alnus glutinosa* - and poplars -*Populus nigra*-) in the Flamisell sampling area and with the dendrogeomorphological years in which damage was detected. The dates of some of the notable flows are indicated, both daily and instantaneous monthly maximums.
Figura 11. Comparación del caudal medio diario y el caudal instantáneo máximo mensual en la estación de aforos 9267-Capdella (Fuente: Anuario de Aforos 2018-2019 «© Ministerio para la Transición Ecológica y el Reto Demográfico», actualización: diciembre 2021) con los periodos estimados de establecimiento de árboles (alisos -Alnus glutinosa- y chopos -Populus nigra-) en el área de muestreo del Flamisell y con los años dendrogeomorfológicos en los que se detectaron daños. Se indican las fechas de algunos de los caudales destacables, tanto máximos diarios como instantáneos mensuales.

Table 7. Accumulated rainfall at Meteocat stations for three selected dates in 2010, in which the maximum rainfall in 24 h was recorded at different stations (https://www.meteo.cat/wpweb/climatologia/el-clima-ahir/climatologia-comarcal/ and https://www.meteo.cat/climatologia/atles_climatic/).
*Tabla 7. Precipitación acumulada en las estaciones de Meteocat para tres fechas seleccionadas del año 2010, en las que las precipitaciones máximas en 24 h se registraron en diferentes estaciones (*https://www.meteo.cat/wpweb/climatologia/el-clima-ahir/climatologia-comarcal/ *y* https://www.meteo.cat/climatologia/atles_climatic/*).*

Dates	Meteorological stations and daily accumulated rainfall (mm)						
	La Seu d'Urgell	Salòria	Sort	Espot	Boí	El Pont de Suert	La Pobla de Segur
09/06/2010	26.2	60.3	56.3	95.1	60	39.8	25.4
22/07/2010	19.5	18.7	45.8	37.4	34.5	53.9	1.2
02/11/2010	0.4	8.6	17.6	15	26.9	27.5	49.9

Table 8. Monthly contributions in Hm^3 at station 9181 - La Pobla de Segur (1965-1991).
Tabla 8. Aportaciones mensuales en Hm^3 en la estación 9181 - La Pobla de Segur (1965-1991).

Measured parameter	Contribution (Hm3)	Month/year; period
Maximum monthly contribution	50.458	June/1979
Minimum monthly contribution	1.991	October/1985
Average monthly contribution	14.927	1965-1991

5. Discussion

5.1. Dendrogeomorphology and flood events

The first objective of a dendrogeomorphological study is to adequately select the sampling areas and species, a process that entails a series of limitations. In the search for areas where trees can provide a record of past floods, forested areas near riverbanks and streams are selected if they include externally damaged trees affected by floods. Various factors act on the evolution and development of riparian forests, but large flood events can destroy or partially eliminate them, with the loss of evidence of previous events and the subsequent establishment of a new forest of uniform age or "cohort" (Oliver & Larson, 1996). It can be especially significant in narrow and steep channels in mountainous areas. In fact, in these contexts, the flood events that are best recorded as damage to trees are those of intermediate magnitude, since the larger ones may destroy all the vegetation and the smaller ones leave little evidence (Ruiz-Villanueva, *et al*., 2010; Génova, *et al*., 2015).

In this sense, the estimated dates of the establishment of the trees in the different areas studied in the upper catchment of the Noguera Pallaresa River present great differences. In the Romadriu subcatchment and, more specifically, in the riparian forest of the Portainé stream, it was determined that most of the trees had progressively established themselves in the alluvial cone since the early 1950s (Génova, *et al*., 2018). During the previous decades, the western margin of the stream probably underwent intensive cultivation (remains of the ancient presence of fruit trees are still found today, García-Oteyza, *et al*., 2015). When agricultural activity ceased, the area was colonized by natural vegetation, as evidenced by the analysis of orthoimages from different years (Génova, *et al*., 2018). On the other hand, the maximum ages estimated in this work for the trees of the Flamisell subcatchment are much more recent, which indicates an almost simultaneous establishment in the 1990s (Table 3), and is, therefore, a clear indication of the great devastation caused by the flood of 1982.

The large flood of 1982 was the last of the three exceptionally destructive events that occurred in the Noguera Pallaresa during the 20th century, in 1907, 1937, and 1982 (Balasch, *et al*., 2008), although no dendrogeomorphological evidence of the first two has been identified. The extensive devastation caused by the 1982 event has been documented, for example, in the Servei Geològic de Catalunya, (1983), in Corominas & Alonso, (1990), and in Balasch, *et al*., (2008). Documentary information indicates that the analyzed area of the Flamisell subcatchment was deforested when the weir was built in the 1920s (Figure 7); likewise, with a subsequent aerial photograph taken in 1956, and especially with further photographs of the 1982 flood up until the late 1980s (Figure 8), from when the establishment of the riparian forest started again. However, even though during this event the transport of materials in the Romadriu River was enormous, producing a ~10 m high dam that blocked its mouth in the Noguera Pallaresa (Figure 6), scars on trees established earlier in this subcatchment have not been dated. Most of these trees were over ten years old at that time (Table 3) and already constituted a more or less homogeneous forest in the Portainé stream, and they did show other evidence (suppressions and releases) affected growth from the following year in more than half of the trees analyzed (Génova, *et al*., 2018), but not in the other studied areas of the Romadriu basin.

5.2. Dendrogeomorphology and flood events

In the dendrogeomorphological dating of flood events, we use the proposal put forward by Génova, *et al*. (2018); i.e. a biannual denomination that corresponds to the dendrogeomorphological year. This biannual dating shows that the event, and therefore the damage caused, may have occurred from the beginning of the dormant period of the trees, which in these latitudes approximately coincides with the end of the summer period, and up until the end of the annual growth. Furthermore, this establishes a coincidence with the hydrological year in Spain, which covers the period that runs from October 1st to September 30th of the following year.

Numerous dendrogeomorphological indicators have made it possible to date important events in the Romadriu subcatchment (Table 4), to which must be added an event that occurred in 1969-70, when many trees in the Portainé stream may have been decapitated (Génova, et al., 2018). The new data presented here do not modify the dates of the evidence gathered from the Portainé stream but increase its amount and reliability, as in the case of the dendrogeomorphological year 1997-98 (Table 4). Among all these indicators, those dated 1997-98, 2007-08, and 2009-10 stand out, due to the greater abundance of recorded evidence, especially scars. While some coincident damages were identified in the Flamisell subcatchment, the greatest correspond to the dendrogeomorphological year 2014-15, when up to 72 % of the trees analyzed presented wounds and bark removal that in some cases reached up to a height of 2 m (Figure 2).

The coincidence of damage in the same dendrogeomorphological year in both subcatchments (Flamisell and Romadriu) does not necessarily imply that they were the consequence of the same precipitation episode that generated simultaneous floods, but may correspond to different events. As already indicated in the previous section, the dendrogeomorphological record of flood events entails limitations, since there does not necessarily have to be a direct correlation between the confirmed dates of the major events and the number and extent of dendrogeomorphological evidence (Ruiz-Villanueva, *et al*., 2010). Thus, for example, the effects of successive events can be masked when two floods occur in the same dendrogeomorphological year, or when the later event of greater magnitude destroys all the dendrogeomorphological evidence of a less intense previous event (Ballesteros-Cánovas, *et al*., 2013). Moreover, the most recent damages (which occurred one or two years before) are very difficult to date, because the callus still cannot be properly identified (Génova, *et al*., 2018).

Another limitation is related to the impossibility of developing reference chronologies to contrast the undisturbed and disturbed tree-ring series, due to the lack of sufficient undisturbed trees in the studied sites. This has been offset by with the contrast of the data on growth anomalies between different species with different ecological ranges. Therefore, whenever possible, it will be more explanatory as well to use temporally detailed documentary and instrumental data that can be related to dendrogeomorphological evidence.

5.3. Comparison of different data sources

When contrasting dendrogeomorphological evidence and data from instrumental records in mountainous areas, it is necessary to take into account that the rainfall in those areas is strongly conditioned by the orography, which generates high-intensity rainfall nuclei, while in neighboring areas the rainfall may be much lower. In the November 1982 event, the inhabitants of the Romadriu Valley explained that the storm stagnated and precipitated directly, hitting the south-facing slope (opposite to the slope where the Portainé and Ramiosa streams are located). This matches the work by Trapero, *et al*., (2013b), in which simulated rainfall at the head of the Romadriu was much higher than in the small streams of Portainé and Ramiosa. The extreme rainfall of 1982 at the head of the Romadriu subcatchment produced the erosion and transport of readily available sediment, which generated the aforementioned obstruction at the confluence with the Noguera Pallaresa. On the other hand, in the case of the Portainé and Ramiosa torrents, only local erosions on the forested banks may have occurred, as well as the possible uprooting and transport of some specimens, consequently giving rise to suppressions and releases, but without enough damage to enable detection in the current riparian forest.

The dendrogeomorphological evidence of 1997-1998 in Portainé (Génova, *et al*., 2018) and in other areas of the Romadriu subcatchment are correlated with significant regional rainfall and flooding. In the Flamisell subcatchment, gauging station 9267 - Capdella recorded a maximum daily instantaneous flow on 18/Dec./1997, although no dendrogeomorphological evidence of this exists. Curiously, it was during the establishment of poplars and alders in the sampled area (1992-1999) when the highest flow peaks of the series occurred, including that of 1997 (Figure 11). Given their youth, shortness, and flexibility, it is likely that the trees leaned against possible floaters, so it is not possible for damage or other evidence to be identified.

In the small Portainé subcatchment, documentary data made it possible to determine in detail the exact date of recent local floods (García-Oteyza, *et al*., 2015; Génova, *et al*., 2018; Furdada, *et al*., 2020). In 2008 and 2010, two floods occurred each year, which were recorded in the dendrogeomorphological years 2007-08 and 2009-10. In the Flamisell subcatchment, the documentary data (Figures 10 and 11) do not clearly coincide with a notable flow peak at the gauging station, although a certain increase in discharge was recorded in spring. Furthermore, the meteorological event of 1-2/Nov./2008 was of a regional nature (Bech, *et al*., 2011; Trapero, *et al*., 2013a) and may have produced a flood peak, although no discharge data is available. Therefore, the wounds in the Flamisell sampling area could have been caused by at least one of these two events or by both, and it is possible that the regional event affected both subcatchments (Romadriu and Flamisell). Damage was caused to the trees of Romadriu and Flamisell in the dendrogeomorphological year 2009-10. The meteorological events that affected Portainé were of a local nature, while the damage to the Flamisell vegetation could be explained mostly by the regional rainfall on 06/09/2010 (Table 7). From 2010 to 2015, the rainfalls recorded in the Romadriu subcatchment were not extraordinary. The local precipitations occurred in July 2011 and 2013 and in August 2014 and 2015 (less than a 10-year return period, although very intense (Furdada, *et al*., 2020), causing debris flows in the Portainé stream (ICGC, 2013a, b; IGC et al., 2013; Palau, *et al*., 2017), and some evidence of damage was observed in September 2015 (Génova, *et al*., 2018).

On 17-18/June/2013, there were significant rainfalls and snowmelt in the Val d'Aran and the headwaters of the Noguera Pallaresa and Flamisell, which caused significant flooding in the Val d'Aran (Victoriano, *et al*., 2016). At gauging station 9267 - Capdella, a significant flow peak was observed, higher than those of 2007, 2008, 2011, and 2015, although no flooding is documented for that occasion. In the sampling area (18 km downstream) there were no tree damages, possibly due to the attenuation of the flood. Conversely, in those other years, the precipitations may possibly have affected a significantly greater area of the subcatchment and the flow increased downstream, thereby causing damage to the trees.

The "Singular weather events" of 27/Nov.-01/Dec./2014 and 10-25/March/2015 could have caused the serious damage detected in the Flamisell forest (the dendrogeomorphological year 2014-15). The gauging station data indicate slight but unremarkable increases in flow. In both events, rainfall data presented maxima at the stations located to the north and west of the subcatchment (Tables 5 and 6). The contribution of flow from the Bòssia River (the tributary on the right bank of the Flamisell that drains ~20 % of the subcatchment; Figure 1) may have led to a significant increase in discharge but went unrecorded at the gauging station because it was located upstream from the confluence.

Despite the floods that caused wounds and other damage between 2008 and 2015 in the forest sampled in the Flamisell subcatchment, the vegetation has since then been densifying, which implies that: 1) the floods that caused the damage were of magnitudes less than that of 1982 when the riverside forest was devastated; 2) the weir has no regulatory role in or influence on these floods of intermediate magnitudes (nor, of course, in extreme ones), and its lamination capacity when a flood occurs is practically nil. In consequence, it does not prevent injuries or other evidence on trees.

Furthermore, it should be noted that, in general, the data from the 9267 - Capdella gauging station provide little or no useful data for interpreting the damage to the vegetation in the sampling area. None of the notable flow peaks indicated in Figure 11, except those of 25 and 27/May/2008, seem to correspond to the damage recorded. This is most probably because an extensive area of the subcatchment is downstream from the station, so the events that affect the headwaters are attenuated downstream and those that are regional and affect the entire subcatchment are underestimated. In the sampling zone, which is close to the mouth, dendrogeomorphological damage is recorded when extraordinary floods occur, but in the case of extreme floods, such as that of 1982, the evidence is destroyed. In addition, the information of a meteorological nature entails the limitation of the location of the stations. As commented above, the orography of the area gives rise to a highly heterogeneous rainfall pattern (Tables 5 and 6). Thus, the data from stations outside the catchment of interest provide only a general idea of the events of a regional nature (and not always), and if they are of a local nature they may not be recorded. If the catchment is very small, as is the case of the Portainé, the best indicator of its dynamics is the dendrogeomorphological data; a rain gauge will only provide really relevant data when it is located at the headwaters. If the subcatchment is larger, as is the case of Flamisell, the local events or those that affect only part of the subcatchment may generate attenuated flows downstream.

The wide and diverse set of data analyzed enables a more comprehensive knowledge of torrential flood dynamics in both subcatchments, which respond to a very inhomogeneous mountain rainfall events. Moreover, the documentary data, both scientific and testimonial, reinforce, complete, and outline the interpretation of the dendrogeomorphological results.

5. Conclusions

Floods that occurred in the upper catchment of the Noguera Pallaresa, specifically involved in the Flamisell and Romadriu subcatchments, are analysed using different data sources. In this and other mountain areas, precipitation is very heterogeneous because of orography and aspect, so the dynamics of small and medium-sized catchments are strongly conditioned by these effects. Thus, instrumental data (meteorological and gauging stations) may or may not reflect the hydrological dynamics of the catchments, depending on their location. The lack of both rainfall and gauging stations often greatly limits the characterization of small and intermediate catchments, such as those in this work, and the use of existing data may lead to impasses or misinterpretation. Dendrogeomorphological and documentary data and geomorphological analyses are therefore essential, and all the available data is required to assess the dynamics.

In this sense, the flood that occurred in 1982, which was exceptionally destructive, showed great differences in dendrogeomorphological evidence between the two subcatchments studied. In the Romadriu subcatchment, no scars on trees were caused, although some trees displayed certain growth anomalies, most probably due to a lower rainfall over the subcatchments of the small tributaries studied and did not generate destructive floods, although it is difficult to explain why the surviving trees in the main corridor of the Romadriu present no evidence of damage. However, in the case of the Flamisell subcatchment, the detailed study of the tree ages reveals that the establishment of the riparian forest started after this flood, highlighting the importance of this type of evidence in dendrogeomorphological studies. Moreover, the dendrogeomorphological evidence registers particularly well other important regional floods, although not as extreme, such as that in 1997, in the Romadriu subcatchment. Regarding the most recent local floods, certain coincidences exist between the dendrogeomorphological years in which damage to the trees was dated. However, it is necessary to point out the extensive damage produced at the Flamisell site in the dendrogeomorphological year 2014-2015, with little or no evidence in the Romadriu subcatchment.

Other selected sources of information (documentary, meteorological and hydrological), often scarce or incomplete, show that it is not necessary for there to be a coincidence in the dates of the high rainfall that caused damage in the different subcatchments. The orography gives rise to a highly heterogeneous rainfall pattern, and the meteorological data provide only a general idea of the events of a regional nature (and not always). When rainfalls are of a local nature, they will not be registered if there is not a station specifically located at the head of the subcatchment to record them. Whenever possible, the use of temporally detailed documentary and instrumental data that can be correlated with dendrogeomorphological evidence will also prove to be more explanatory. If the catchment is very small, the dendrogeomorphological data would probably be the best indicator of floods; but if the subcatchment is larger, the local events or those that affect only part of the subcatchment may generate attenuated flows downstream that do not result in damage to the riparian forest.

The integration of different types of data and methodologies, therefore, continues to be of unquestionable value for broadening the knowledge of and characterizing the dynamics of mountain catchments. In this regard, the documentary data, both scientific and testimonial, reinforce, complete and outline the interpretation of the dendrogeomorphological results.

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