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Long-term entrenchment and consequences in present flood hazard in the Garona River (Val d'Aran, Central Pyrenees)

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Abstract

On 18 June 2013, a damaging flood of the Garona River (Val d'Aran, Central Pyrenees, Spain) caused losses exceeding EUR 100 million. Flood events are rarely related to the geologic, tectonic and geomorphologic context. This study bridges the gap between the short- and long-term processes scope. The upper reach of the Garona River was studied considering different space and time scales in order to establish a relationship between present short-term fluvial processes and the long-term evolution of the area. There is a clear entrenchment tendency of the drainage network since the Miocene. Post-orogenic exhumation and uplift of the Axial Pyrenees proves the recent and active tectonics of the area which leads to valley entrenchment. The last Upper Pleistocene glaciation affected the Aran valley and gave rise to a destabilisation period during the glacial–interglacial transition, characterised by a postglacial incision tendency. Mean entrenchment rates between 0.68 and 1.56 mm yr^{-1} since deglaciation have been estimated. During the Holocene, the valley evolution is mostly marked by vertical incision and recent fluvial dynamics is characterised by the predominance of erosive processes. The 2013 flood produced lateral and/or vertical erosion along almost all the river length in Val d'Aran. These results suggest that the long-term tendency of the fluvial system is reflected in short-term processes. Thus, understanding the fluvial network development and evolution of the upper reach of the Garona River will serve to predict river response during flood events. This study helps to improve flood risk management, which needs to take into account the long-term river dynamics.

1 Introduction

Floods are one of the most dangerous and relatively frequent natural disasters, as they produce severe effects for humans and health, as well as socioeconomic, cultural, geomorphologic and environmental impacts, especially in urbanised areas. According to the Civil Protection National Plan for Flood Risk (Plan Estatal de Protección Civil ante el Riesgo de Inundación, 2011), floods constitute the most frequent and damaging geological risk in Catalonia (Spain).

Val d'Aran (Aran Valley) is susceptible of suffering mountainous torrential flooding events. The Emergency Flood Plan of Catalonia (Protecció Civil, 2015) classifies this basin as a high flood risk area. In fact, during the 20th century, three extraordinary flood events occurred in 1937, 1963 and 1982 (Piris, 2013; García-Silvestre, 2014), showing a high recurrence. The last event was a devastating flash flood in the summer of 2013, which caused damages throughout the Garona (Garonne) River and some of its tributaries. Meteorological and hydrological causes of the 18 June 2013 floods in the Aran valley have been accurately studied in a multidisciplinary work carried out by the Servei Meteorològic de Catalunya (SMC), the Servei de Predicció d'Allaus de l'Institut Geològic de Catalunya (IGC) and the Agència Catalana de l'Aigua (ACA) (Pineda et al., 2013). According to these authors, heavy rainfall (120 mm in 48 h, 100 mm of them in 24 h) and fast melting due to a temperature increase after an unusual heavy snow period should be regarded as the triggering factors for the 2013 flood. However, real data show that water discharge was lower than those recorded during known historical floods. The main geomorphological effects were lateral and vertical erosion, debris accumulation, shallow landslides and torrential flows, and reactivation of some alluvial fans (IGC, 2013). Damages in anthropogenic facilities were also recorded, such as in buildings, camp sites, roads, bridges, dams, hydroelectric plants and channelization dykes. Even if there were no fatalities, the total economic losses of these floods reached up to EUR 100 million (Corporació Catalana de Mitjans Audiovisuals [online], 18 June 2013).

Flood hazard depends on fluvial dynamics. However, most of the previous works on fluvial systems exclusively deal with present processes or landforms, whereas other research lines focus on long-term landscape evolution, i.e. the geomorphologic and tectonic long-term processes that shape the landscape. This study bridges the gap between long- and short-term processes, by relating the regional geologic and geomorphologic setting with the present fluvial dynamics and flood events. This approach at different time and space scales allows a better understanding of the basin hydrological system and river response.

The aim of this study is to analyse the long-term dynamics of the Garona River in order to understand present short-term processes. This is achieved by means of the geomorphological analysis (long-term), and by the specific study of present fluvial processes (short-term). The knowledge of the fluvial dynamics at different time scales will improve the flood risk reduction in Val d'Aran. The analysis of the origin and evolution of geomorphic features allows us to understand the long-term fluvial tendency and to determine the entrenchment rate. The analysis of the flood effects and the evaluation of flood hazard allow a better management of the catchment and the design of effective defence strategies.

We consider that the Garona River shows a long-term entrenchment tendency which is reflected in present short-term fluvial processes. So, the flood effects of the 2013 event can be explained in a great extent by the river's entrenchment tendency.

2 Study area

The Pyrenean mountain range, extending for about 435 km in a WNW–ESE direction, is located at the NE of the Iberian Peninsula. Their northern and southern limits are the Aquitaine and Ebro foreland basins, respectively.

Val d'Aran (Catalonia, Spain) is located in the Atlantic side of the Central Pyrenees. It is a 620 km^2 mountainous region with about 30 % of its area above 2000 m a.s.l. (ICC, 1994), with peaks close to 3000 m a.s.l. Therefore, population is mainly settled along the valley bottoms (9993 inhabitants; IDESCAT, 2014), where land use has changed from mostly agricultural towards an increase in urban settlements over the last decades. Because of its northern orientation, the area is characterised by an Alpine Atlantic climate, with high humidity, significant temperature variations (6–10 °C, mean annual temperature), high precipitations (900–1100 mm, mean annual precipitation) and balanced seasonal rainfall pattern. Maximum precipitations in terms of intensity and frequency are recorded in spring and autumn, whereas snowfall precipitation occurs mainly in winter (Protecció Civil, 2015). This mountainous territory corresponds almost entirely to the upper part of the Garona River catchment, whose initial E–W direction (study area A) changes downstream towards a N–S one (study area B). It has a well-developed drainage network, significant gradients (higher than 20 % in some tributary streams) and steep slopes.

In order to study the Garona catchment, and although the 2013 flood produced several damages along most of the major river length, we selected two areas (Fig. 1). They are representative for the whole valley, both in terms of geomorphology (significant geomorphic features) and flood effects (most populated and particularly affected river stretches). Study area A corresponds to the Garona River between the Arties and Vielha municipalities (approximately 8.3 km long), including Garós, Casarilh, Escunhau and Betrén. Study area B, downstream from study area A, includes Era Bordeta, Bossòst and Les (approximately 12 km long). These two study areas will provide relevant and representative information about the Garona River dynamics.

3 Geological and geomorphological setting

The Pyrenees formed as the result of the continental collision between the Iberian and the Eurasian tectonic plates during the Alpine orogeny. This process started in the Upper Cretaceous and continued until the Middle Miocene. The tectonic structure mainly consists of a WNW–ESE thrust and fold system almost parallel to the mountain chain. According to Fontboté (1991), geological materials of the Pyrenees can be grouped in three large units: the basement or Palaeozoic bedrock, including late Hercynian intrusions of granitic batholiths (IGC, 1994), the Mesozoic and Tertiary cover, and the post-orogenic Neogene and Quaternary deposits and landforms. Recent neotectonic studies in the Pyrenees (Lacan and Ortuño, 2012; Ortuño et al., 2013), identified zones indicating a continued uplift related to isostatic processes, and proved the existence of an active tectonics.

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Val d'Aran is located in the so-called Pyrenean Axial Zone, where metasedimentary and metamorphic Palaeozoic basement rocks, deformed during the Hercynian orogeny, and late Hercynian granitic rocks constitute the Lower Thrust Sheets unit. Quaternary deposits (mainly of glacial, fluvial, alluvial and colluvial origin) are common in the valley bottoms, on the slopes and in the higher areas (Fig. 2).

Present landscape of the Pyrenees mostly results from the Upper Pleistocene last glacial period, with scarce and poorly preserved evidences of previous glaciations. Glacial cirques and valleys excavated into previous Neogene high planation surfaces whose remnants are clearly visible in the summit areas (Mianes, 1955; Ortuño et al., 2013). Therefore, glacial sediments and landforms (tills, moraines and rock glaciers), as well as postglacial ones (colluvial and alluvial deposits, lacustrine and peat zones) are the main Quaternary features (Bordonau, 1985, 1992; Serrat and Vilaplana, 1992).

The Aran valley constitutes the upper catchment of the Garona River and, during the last glacial period, represented one of the main accumulation zones of the Garona glacier. This glacier had a length of about 70 km, reaching the Aquitaine basin, and a maximum ice thickness of up to 800 m (Bordonau, 1992). Thus, only evidences for the maximum extent and the latest deglaciation phases are clearly recorded in the Aran valley. Bordonau (1985, 1992) analysed the geomorphological evolution of the Aran valley and distinguished 4 main periods based on the present deposits and landforms:

– Pre-glacial period (Upper Oligocene–Lower Miocene). During this period, extensive planation surfaces were formed. These planation surfaces are nowadays located at altitudes between 2000 and 2200 m.

– Last glacial period (Upper Pleistocene). Some juxtaglacial deposits described in a few localities evidence the existence of a glacial stabilisation previous to the last glacial maximum. A time lag between the maximum ice extent in the Pyrenees (> 40 ka), recorded during MIS 4, and the global LGM culminating ca. 21 ka during MIS 2 (Mardones and Jalut, 1983; Montserrat-Martí, 1992; Bordonau, 1992; García-Ruiz et al., 2003; Calvet et al., 2011; Delmas, 2015; Turu et al.,

2015) has been proved for the whole Pyrenean valleys. In the Garona valley, the glaciolacustrine and till deposits at the base of the Barbazan Lake fill sequence, about 30 km downstream from Les, have yielded an age of 31.16 ± 1.7 ka BP (32.037–39.407 ka cal BP), showing the presence of a glacier on that site until 26.6 ± 0.46 ka BP (29.786–31.446 ka cal BP) (Andrieu et al., 1988; Jalut et al., 1992). ^{10}Be dating indicates that Barbazan Lake was uncovered by the ice retreat by 21.084 ± 0.878 ka (Stange et al., 2014b). However, according to Pallàs et al. (2006), peak glacial conditions were present continuously from the Pyrenean glacial maximum until the LGM, although some ice-boundary fluctuations have been documented. During the last glacial maximum, the Garona glacier (Fig. 3) modelled the Aran valley (cirques and U-shaped valleys) and sedimented tills and related deposits. Following the glacial maximum, several younger deglaciation phases, undated in the Aran valley, can be distinguished due to the presence of well-preserved lateral and terminal moraines corresponding to small valley glaciers (a few km long) and cirque glaciers.

- Late-glacial period (Upper Pleistocene–Holocene). This period is characterised by the presence of abundant rock glaciers together with small cirque glaciers. These rock glaciers were usually attributed to the Younger Dryas (Serrat, 1979) but they might extent into the Early Holocene (Pallàs et al., 2006) until the complete glacial retreat in the Aran valley.

- Postglacial period (Holocene). This period is characterised by geomorphological processes like those active at present, such as periglacial processes, fluvial-torrential action (fluvial erosion and formation of terraces and alluvial fans), slope regularisation, lacustrine environments and so on. All these processes tend to degrade the previous deposits and landforms, and to create new ones.

Hence, the geomorphological features of the study area are indicative of the Garona pre-Quaternary and Quaternary evolution mainly characterised by erosive processes and a progressive fluvial network entrenchment resulting from fluvial-

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torrential dynamics, giving way to alluvial fans, alluvial terraces and floodplains on deeply incised valleys.

4 Methods

The initial document used as a starting point for this work is the preliminary study done by the Geological Institute of Catalonia (Institut Geològic de Catalunya, IGC) in 2013. Topographic and geologic maps were broadly consulted as well.

The geomorphological method was used to produce a geomorphological map of the area and a map of the flood effects. Both maps, at 1 : 5000 scale, were done using ArcGIS® geographic information software from ESRI and online geoservices (WMS) from the Cartographic and Geological Institute of Catalonia (Institut Cartogràfic i Geològic de Catalunya, ICGC). On the one hand, a preliminary geomorphological map of the area was done based on the photointerpretation of stereo-pair aerial images of the 1956–1957 American flight, where the main geomorphological features were mapped (drainage network, ancient channel zones, alluvial terraces and alluvial fans). This map was especially useful to recognise the main natural landforms, with little or no anthropization, which reflect the fluvial-torrential dynamics. On the other hand, a preliminary map of the flood effects was done based on the identification of the erosion, overflow and accumulation areas, as well as preferential flow paths. This digitisation was done by using and comparing the georeferenced ortophotos of 2012 and of the 2013 flood event from the ICGC.

During the subsequent field survey several detailed works were carried out, such as verification of the preliminary geomorphological map, observation of the flood effects in situ, observation and data collection of different erosion and entrenchment indicators, identification of "black points" along the Garona River and the observation of the post-flood defence measures. By integrating all the obtained information, the definitive geomorphological and flood effects maps were obtained.

The dynamics of the Garona was studied through the specific analysis of the identified entrenchment indicators, both long-term (geomorphological features) and short-term (flood effects and field observations). Using the data from topographic maps and field work measures, entrenchment rates were estimated. Besides, the values of fluvial incision in alluvial fans of the Garona tributaries were graphically represented.

Transversal and longitudinal profiles of the Garona River and its tributaries were done using both ArcGIS and Global Mapper software. These sections allowed us to relate the flood effects with the long-term tendency of the drainage network. The necessary data for these topographic sections were extracted from the 5 m Digital Elevation Model (DEM) of 2012 (ICGC).

5 Long-term dynamics of the Garona River

Previous studies by Victoriano (2014) and García-Silvestre (2014) showed evidences of an incision tendency of the Garona River and present clear entrenchment indicators in the Arties-Vielha and the Era Bordeta-Les fluvial stretches. By integrating both previous works within the geomorphological map which is the basis of this study, an initial hypothesis of fluvial entrenchment tendency into the river bed raised.

5.1 Geomorphological analysis

Fluvial systems consist of erosive (e.g., alluvial channels) and depositional (e.g., floodplains, alluvial fans, terraces) features, although human activities, such as increasing sediment loads and building of channels and dams, also impacts on the present fluvial processes (Huggett, 2007). In order to understand the long-term tendency of the Garona River and its natural evolution, we identified, mapped and analysed the main geomorphological features in the study area. The bottom of the Garona valley and the accumulation and erosive features in the lower part of the main

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tributaries were mapped in two selected study areas. We focused on features related to fluvial, torrential and alluvial dynamics (Figs. 4, 5, 6).

- Main drainage network. The course of the Garona River and its tributaries were mapped (not well-defined, inactive or seasonal tributaries are indicated as supposed drainage network). In the study area A, the length of the Garona River is 8.3 km and the vertical drop is 207 m, so that the mean gradient value is 2.5 %. In the study area B, which is 12 km long with an altitude difference of 190 m, the mean gradient is 1.6 %. Nonetheless, the gradient is not uniform all along the studied stretches (Fig. 8). The main channel's width is also variable, being narrower along entrenched stretches. By and large, where the Garona channel is narrower the slope is higher, whereas wider channel corresponds to a slope decrease. Anyway, channel's present morphology is anthropogenically modified in some places, especially in urbanised areas, where the river is confined by channelization dykes or rock embankments. All the tributaries are much steeper than the main river.

- Ancient channel areas. Some low areas which correspond to the natural river channel system were distinguished, as water flow lines were identified in the 1956 aerial photographs. Hence, they are adjacent areas to the main channel through water flows relatively frequently or used to flow in the past (in some cases before channelling). Ancient channel areas are flat areas characterised by being located at a slightly higher altitude than the river bed (0–5 m high, but usually less than 3 m), but lower than the alluvial plain.

- Alluvial terraces. Two alluvial terraces can be distinguished. On the one hand, a low level of alluvial deposits that corresponds to the recent Holocene floodplain, formed by the deposition of materials during flood events. These low alluvial plains, 3–10 m higher than the present river bed, are located discontinuously along both sides of the river and they are generally linked to the main channel or to ancient channel areas (Figs. 4, 5, 6), except for the one in Casarilh and Escunhau.

On the other hand, high alluvial terraces formed during the last glacial–interglacial transition or even the Holocene were identified. They correspond to a valley train or an ancient floodplain that became inactive due to river entrenchment, so they are not linked to channel areas. These terraces are found 15–20 m above the present river bed in the study area A. Only two patches were identified, the first one upstream from Betrén and the second one in Casarilh and Escunhau. The latter was only recognised in the 1956 aerial photographs, but it was not identified in the field, most likely due to degradation and anthropization. In the study area B, however, several terrace patches can be found 10–15 m above the present river bed, especially between Bossòst and Les (Figs. 5, 6).

– Alluvial fans. Alluvial fans are found at the confluence of the main tributaries with the Garona River. In some confluences at the middle and upper parts of the study area A, and all along the study area B, two generations of alluvial fans were identified. The smaller and more recent alluvial fans are emplaced in the distal part of the older and larger ones. Thus, while the stream incises into the old alluvial fan, a new alluvial fan is formed downstream (Figs. 4, 5, 6, 7). In some cases, the two generations of alluvial fans were not identified (e.g., in Vielha), even if the distal part of the first generation alluvial fan is eroded (e.g., in Arties). Concerning the spatial relationship between the alluvial fans and the floodplains and channels, there are clear differences along the analysed river length. On the one hand, in the upper and middle parts of the study area A (except for the Valarties alluvial fan) and in the study area B (except for the left margin alluvial fan at Bossòst), first generation fans do not connect with the channel because their distal parts are strongly eroded, but they can be linked to high terraces, as it occurs in Les (Fig. 6). In these cases, second generation fans tend to be connected to channel areas or floodplains (Figs. 4, 5, 6). On the other hand, in the lower part of the study area A (as well as in the Valarties alluvial fan) and in the left margin alluvial fan at Bossòst in the study area B, large alluvial fans without second generation emplaced fans are generally linked to the channel or

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the floodplain, except between Escunhau and Betrén where the river flows rather entrenched.

- Escarpments of fluvial incision. In many cases, depositional features are heavily eroded. This is the most remarkable feature providing information about the long-term river tendency. Fluvial incision can easily be identified when looking at old alluvial fans on both study areas (e.g., Salider in the study area A, alluvial fans at Bossost in the study area B; Figs. 5, 7) but also in some high terraces (e.g., Betrén in the study area A, upstream from Les in the study area B; Fig. 6).

5.2 Entrenchment indicators analysis

The long-term entrenchment tendency of the Garona River is evidenced by three main features: the existence of two generations of alluvial fans and terraces, the incision in alluvial fans and terraces, and the entrenchment in bedrock.

- Two generations of alluvial fans and terraces. Geomorphological maps show alluvial fans and terraces of two different generations. On the one hand, we identified younger alluvial fans inserted into the oldest ones as a result of a change in the channel position due to river entrenchment and the consequent stream entrenchment (in some cases deeper than 20 m, as in the alluvial fan at Bossòst). However, the decrease of the sediment load from tributaries also affects in this process (see Sect. 7). On the other hand, we found high alluvial terraces that, although they correspond to the same postglacial terrace system, indicate a river entrenchment along time. In fact, as the river entrenched the ancient floodplains or valley trains (the present high terraces) were abandoned and new floodplains (the present low terraces) were formed. An important fact is that these two alluvial levels were formed after the retreat of the last Pleistocene glacier, as discussed below.

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– Incision in alluvial fans and terraces. Some geomorphological features show a metric to decametric escarpment as a result of fluvial incision. In some cases, alluvial fans are cut in their distal part. The height of these escarpments is up to 35 m (15–35 m depending on the site). In the case of the high terraces, the incision is 10–20 m high, being higher in the study area A. The high terrace located upstream from Betrén (study area A) shows a 15–20 m escarpment, whereas in the study area B they show a 10–15 m escarpment, as in the right side of the Antòni tributary upstream from Les.

– Entrenchment in bedrock. Palaeozoic basement rocks were identified in the river channel margins in some sites, indicating a very high river erosive power. Where the Salider stream meets the Garona (study area A), bedrock crops out in the left side, whereas in the right side there are recent alluvial deposits. The Garona is also entrenched into the bedrock at Betrén, where the river eroded all the alluvial fan deposits reaching the Palaeozoic basement, and continued entrenching through the slates and schists, generating an up to 20 m high escarpment.

Among all these indicators, high alluvial terraces are the most significant ones. In fact, incision in alluvial fans is influenced by the particular size and shape of the fan and the evolution of the Garona channel location. Even though they indicate strong and differential fluvial incision, they cannot be used to calculate entrenchment rates.

High alluvial terraces indicate that the river has entrenched 10–20 m in the study areas, so they are useful to calculate the river entrenchment rate since their formation. In the study area A, the high terrace at Betrén, the most representative one, indicates a fluvial erosion between 15 and 20 m since its formation. These terraces formed shortly after the glacier retreat. The Garona glacier retreated from Barbazan, about 53 km downstream from Betrén, at ca. 21 ka (Stange et al., 2014b), so our study area was deglaciated later. No absolute ages are available for deglaciation stages in the Aran valley but, according to ages obtained in the contiguous southern Noguera Ribagorçana glacial basin (Pallàs et al., 2006), the Garona glacier would have retreated upstream from Betrén between 14.6 and 12.8 ka (see Sect. 7). Assuming a constant entrenchment, the obtained approximate mean entrenchment rate of the Garona River is between 1.03 and 1.56 $mm\,yr^{-1}$. In the study area B, high alluvial terraces are found 10–15 m high above the present river bed, yielding an average entrenchment rate between 0.68 and 1.17 $mm\,yr^{-1}$.

The magnitude of vertical erosion data does not show a uniform spatial distribution. Generally the steepest stretches are the most entrenched ones (e.g., downstream from Garós), whereas stretches where the slope decreases show a certain accumulation tendency (e.g., the Prado Verde campsite at Era Bordeta). This differential entrenchment is clearly reflected in the incised alluvial fans of the main tributaries. The highest incisions are found in the study area A, so we analysed escarpment values there (Fig. 8). The highest escarpments were formed in the right side of the upper part of this study area (e.g., 25–35 m in the Salider alluvial fan). Downstream and in the Garona's left side, values are lower (e.g., 15 m in the Betrén alluvial fan). Thereby, there is clear evidence of entrenchment in the upper part and in high terraces, but not in the lower part, where the alluvial fans are not eroded. Nonetheless, we need to be careful when interpreting this data, as these differences may depend on several factors, such as the thickness and morphology of the alluvial fan and/or the amount of available material in each tributary catchment area.

Smaller and younger alluvial fans were formed in many of the eroded alluvial fans. In these cases, the inactivity of the first generation of alluvial fans and the formation of the second generation of them can be explained both by the river entrenchment and the lack of sediment load to keep them active. However, in some cases, alluvial fans from the first generation tend to be linked to the channel area or to the low alluvial plain. This can be the result of a sediment input rate higher than the local entrenchment rate. Therefore, more exhaustive studies would be necessary to determine the causes for the differential incision observed along the study area.

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6 Present short-term processes

During the 2013 flood, erosive effects dominated overflow ones (García-Silvestre, 2014; IGC, 2013; Victoriano, 2014), suggesting that long-term dynamics is reflected in present fluvial processes and flood hazard.

6.1 2013 flood effects

The origin and type of the 2013 flood effects are diverse, but they occurred in areas where flood hazard was known and foreseeable (Oller et al., 2013). The aim of identifying, mapping and analysing the main flood effects is to know the present tendency of the fluvial system during flood events. Flood effects (e.g., erosion and accumulation areas, flooded areas, flow paths) were mapped along the Garona River and its main tributaries in both study areas (Figs. 9, 10).

- Main drainage network. The channels were mapped as the areas of major water flow. The Garona course during the flood event shows two important features. The first one is the channel modification, including widening along almost all the river length, produced by the margin erosion, and also deepening in some stretches. The second one is the avulsion that occurred in some places where the Garona changed its previous path (e.g., downstream from Arties in study area A, and the meander at Era Bordeta in study area B).

- Erosion areas. Eroded margins during the 2013 event were mapped (Figs. 9, 10), comparing the 2012 and 2013 ortophotos. Fluvial erosion was one of the most devastating effects causing severe damages in urbanised areas, especially in Arties (Fig. 11), Bossòst and Les (Fig. 12). An important part of the river margins were heavily eroded during the 2013 extraordinary event. In order to quantify the erosion, we considered the Garona River along the two study areas and the lower stretch of the Valarties River. 44.3 and 46.3 % of the total length of the margins of the studied areas A and B, respectively, correspond to eroded margins

(Table 1), reflecting the significant magnitude of erosive processes. However, these are minimum values because in some stretches riverbank trees made it difficult identifying the erosion in the ortophoto, and moreover, some places were not accessible during field survey. Erosion escarpments are generally not higher than 1 m, although they can be higher in some cases.

- Accumulation areas. A small part of the flood prone area was covered by muds, sands, gravels, cobbles and/or wood transported by the Garona River and its tributaries; in fact, 13 and 25 % of the flood prone area in study areas A and B, respectively (Table 2). Accumulation is mainly explained by the decrease of the flow speed due to a slope decrease and/or to confluence areas. Two extensive accumulation areas were identified. The first one lies on the right riverbank downstream from Arties (study area A), where the Era Yerla campsite was placed. A slope decrease can be observed in this area (Fig. 8), where the Valarties tributary river joins the Garona. The extension of this accumulation area is about 55 000 m^2 (50.3 % of the total accumulation area in the study area A). The second one is the Prado Verde campsite in Era Bordeta, where materials were deposited occupying about 80 000 m^2 (23 % of the total accumulation area in the study area B). In these two sites, thicknesses of up to 2 and 1.5 m were measured, respectively.

- Flooded area and preferential flow paths. Reconstruction of the flooded area and preferential flow paths during the 2013 flood event was based on the analysis of the ICGC flood ortophotos, data from the IGC (2013) preliminary study, field survey carried out after the 2013 flood, geomorphological mapping and information provided by witnesses. Water flooded channel adjacent areas, such as in Arties, the Vielha industrial park, Bossòst and Les. Flooding can be related to overflow or river widening by margin erosion. In the study area A, the estimated flooded area is about 367 100 m^2 (43 % of the total flood prone area), whereas about 483 400 m^2 (35 % of the total flood prone area) were flooded in the study area B (Table 2). Nevertheless, these are minimum flood extension values.

– Activity in alluvial fans. Downstream from Arties (study area A) we identified the reactivation of the distal part of the Salider alluvial fan. Debris flows occurred during the 2013 event in some tributary catchments, increasing the sediment load of the stream and leading to fan reactivation and deposition. The active part of the Salider alluvial fan occupied about 1700 m^2, 3.5 % of the total area of the most recent (second generation) alluvial fan. The first generation alluvial fans were not active during the 2013 flood event but some of them showed activity during other historic floods (e.g., the Nere River in 1982).

Considering all the analysed effects, we emphasise that erosive processes are relatively more important than overflow ones. In fact, lateral erosion and widening of the channel occurred almost along the whole study area.

6.2 Erosion and entrenchment indicators analysis

In addition to the lateral erosion of the margins (see Sect. 6.1), flood effects and other field observations in anthropogenic hydraulic structures along the study area allowed us to identity some features that indicate the predominance of erosion and incision processes.

– Vertical incision below bridges and channelization dykes. Engineering structures in river channels commonly show how the river entrenches into its bed. Several points were found along channelized stretches where the river eroded below the foundations of lateral dykes. The channelized stretch along Les shows the best example of vertical incision below dykes (Fig. 13), where part of the dykes collapsed two days after the 2013 flood peak due to the loss of basal support (Fig. 12). Besides, erosion below pillars was identified in some bridges, as the one in Garós, where the river has incised almost 2 m since it was built, eroding

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the concrete and even 1.5 m of fluvial materials, so new foundations had to be reconstructed.

- Erosion related to gauging stations and dams. Gauging stations and dams are hydraulic structures where the river bed is impermeable, avoiding natural entrenchment and hence, favouring fluvial erosion downstream them, either by turbulent flow or hungry water erosion. Anyway, in some cases incisions can be also observed upstream, even if their magnitude tends to be lower. At some sites, fluvial erosion was high enough to show outcrops of tills beneath the fluvial sediments. Immediately downstream from the Valarties gauging station (Fig. 14a), an erosion around 3 m was measured, showing a thin outcrop of alluvial and glacial deposits. However, incisions were also identified upstream from the gauging station (Fig. 14b), where the erosion cannot be explained by local turbulences. At the Arties dam, incisions between 0.4 and 1 m have been formed in both river margins since it was built, allowing tills to outcrop.

Although erosion in hydraulic structures can be strongly influenced by local conditions, it clearly indicates an erosive fluvial tendency. Anyway, given their characteristics, the examples described above cannot be used to calculate entrenchment rates.

7 Discussion

This study proves that the Garona River shows evidences of a clear entrenchment tendency at least since the end of the last glacial period. Moreover, other regional studies confirm that this tendency can be recognised over different time scales, in fact, since the Miocene. This dynamics needs to be taken into account for flood risk management strategies.

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7.1 Active tectonics and entrenchment

The Pyrenees is a mountain region with low present deformation rates. Lacan and Ortuño (2012) distinguished two main domains related to different isostatic rebound: the High Chain (where Val d'Aran is located), where active faults are controlled by vertical maximum stresses, and the Low Chain, where horizontal maximum stresses of variable orientation seem to be dominant. Even though they admit that further research is needed to better characterise the active faults, seismicity and uplift of the chain, they consider the Pyrenees as an active mountain belt. This activity is proved by several sources and methods, such as the instrumental continuous seismic activity, the historical seismic record (e.g., the earthquake that affected Vielha in 1923), the postglacial fault displacement (e.g., in the Maladeta Massif, SW Val d'Aran), the post-orogenic surface uplift (> 0.5 km, and up to 2 km since the late Miocene at several sites), and data on post-orogenic enhanced exhumation. They affirm that in addition to the topographic gradient leading to the river entrenchment, other factors such as successive glaciations and periglacial weathering accentuated the erosion in the High Chain, what probably resulted on a differential uplift by isostatic compensation.

Placing our study area in the whole context of the Garona River drainage system, more evidences that reinforce the idea of this entrenchment tendency can be considered. The important erosive phase in the High Chain after the Alpine orogeny compressive period, consequently formed huge alluvial fans in the Aquitaine foreland basin (e.g., the molasse-fan of Lannemezan), from the late Miocene up to the Pliocene (Stange et al., 2014b and references therein).

According to Ortuño et al. (2013), the Prüedo lacustrine deposits, at about 3 km southeast of the study area A (Fig. 2), can be related to a planation surface originally located at lower altitudes, thus proving the regional uplift of the area since 11.1–8.7 Ma (Middle Miocene). Moreover, this study also notes that a 2–3 km thick material removal has occurred in the last 10 Ma. This exhumation can be first explained by the regional uplift and, secondly, by the activity of the North Maladeta Fault. Thus, erosion and exhumation induced the post-orogenic uplift of Central Pyrenees due to the isostatic compensation, with an estimated uplift rate between 0.08 and 0.19 $mm\,yr^{-1}$ (Ortuño et al., 2013). Uplifted regions commonly show fluvial-torrential incision, as there is not enough time for slope regularisation processes (Turu and Peña, 2006).

Moreover, Stange et al. (2014a) perform an exercise in model exploration to evaluate stream profile development under potential scenarios (climate change, tectonic and isostatic uplift, and lithological contrasts) in the Ebro foreland basin. This simulations include tributaries whose headwaters are in the Central Pyrenees (e.g. the Noguera Ribagorçana River, south of the Val d'Aran). According to Stange et al. (2014a), the progressive entrenchment of the Ebro river network could be related to tectonic uplift amplified by erosional isostatic rebound. In agreement with model-based results obtained by Vernant et al. (2013), long-term regional landscape denudation induces relatively uniform isostatic uplift in the Ebro foreland basin, which gradually increases towards the Pyrenees crest zone where the largest sediment volumes are excavated. Thus, regional tectonic (and also isostatic) uplift affects the Pyrenees and the Ebro and Aquitaine foreland basins, providing a mechanism also for the valley entrenchment in the northern Pyrenees.

Therefore, the tectonic–isostatic evolution of the Axial Pyrenees could partially explain the entrenchment dynamics of the drainage network in the studied area. Moreover, it is well known that incision remains dominant in uplifted regions throughout cold and temperate periods as long as the rivers are in an unsteady state (Vandenberghe, 1995).

7.2 Postglacial geomorphological evolution

All the obtained information allows us to characterise the Garona evolution since the postglacial drainage network was developed until present. Understanding the links between climate and fluvial system evolution has been the target of many studies.

Traditional climatic theories since the beginning of the 20th century supported the idea of a direct relationship between glacial periods and sedimentation (aggradation),

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as well as interglacial periods and entrenchment (incision) (Vandenberghe, 2002 and references therein; 2003). Several statements against this classic theory have proved that fluvial response to climate changes is neither direct nor linear, but a complex response consisting of non-linear morphologic changes and a gradual evolution of the system (Vandenbergue, 1995). In fact, some magnitude and duration threshold values need to be exceeded for climatic variations in order to produce changes in fluvial activity and morphology (Vandenbergue, 2002), so that fluvial dynamics is controlled by the time scale, duration and magnitude of changes on climate. Furthermore, fluvial development is not solely climate-dependent, but apart from climatic parameters (rainfall and snowfall), also a number of climate-derived factors (energy, sediment input, permafrost and water underground storage), partially climate-dependent factors such as vegetation cover, and non-climatic factors (morphometric characteristics of catchments, response time, threshold values, tectonics and anthropogenic influence) play an important role (Vandenbergue, 2003). This all proves that in some cases the influence of climate can be minimal.

During the last glaciation (Upper Pleistocene), the Garona glacier extended ca. 70 km reaching the Aquitaine foreland basin (Mianes, 1955; Calvet et al., 2011; Stange et al., 2014b and references therein; Delmas, 2015). In the Aran valley, located at the upper part of the glacial basin, a minimum ice thickness of about 800 m has been estimated between Vielha and Les Bordes (Fig. 3) (Bordonau, 1985), about 18 km downstream from the glacier head. During the last glacial maximum, cirques and U-shaped valleys were eroded and extensive subglacial till covers where deposited. Glacier retreat during deglaciation allowed the development of a fluvioglacial drainage network, while decompression and slope fracturing, and intense erosion of tills covering the slopes started. This last glacial–interglacial transition appears to be a major disequilibrium period in the whole Pyrenean region.

As it is well known, at the snout of a glacier ablation processes cause supraglacial and englacial debris to accumulate on the ice surface, and the role of meltwater increases towards the snout where it does more geomorphological work than the ice itself (Selby, 1985). Fluvioglacial deposition is dominant in the proglacial zone because of the rapid dumping of these large quantities of coarse debris immediately beyond the glacier margin, where the associated shifting of stream channels produces extensive depositional plains or valley trains (Summerfield, 1991). All these processes most likely happened in the Aran valley during deglaciation, enhanced by the large amount of glacial sediments being exposed, destabilised and eroded as the trunk Garona glacier and its tributaries retreated. Thus, high sediment load and discharge flow allowed the formation of large first generation alluvial fans at the confluence between the steeper tributaries and the gentler Garona River, during a first very active stage.

About 21 ka ago, the Garona glacier retreated upstream from Barbazan (Stange et al., 2014b), further downstream from the Aran valley (30 km downstream from Les). Thus, deglaciation in the Aran valley must be younger, probably around 13.7±0.9 ka BP as in the neighbour southern Noguera Ribagorçana glacial basin (Pallàs et al., 2006). Therefore, the formation of both the highest terrace level and the first generation of large alluvial fans, which are topographically connected (Fig. 6), took place between ca. 21 and 13.7 ka, depending on how fast the glacier retreat was, as soon as the glacier uncovered the valley bottoms.

After this initial phase of rapid and generalised alluvial deposition, material availability in the tributary catchments decreased and, therefore, stream and fluvial activity turned to incise. The distal parts of most first generation large fans were cut, their main channels entrenched and the fluvioglacial deposits incised resulting in the highest terrace level. This incision could be stepped-up by the rebound effect produced by the decompression on the valley bottom after the glacier retreat and by the active tectonics (see Sect. 7.1). This second stage supports that climatic glacial to interglacial transitions correspond to instability phases and, often, to river incision (Vandenberghe, 2002). At this stage, smaller second generation alluvial fans, fitted into the older ones, were formed in some confluences, reaching lower topographic levels as the Garona River incised itself. Not all large first generation fans present second smaller fans and, in this case, they connect with the present alluvial plain (see Sect. 5.2). Finally, the main drainage network dynamics turned to be marked by the alluvial plain generation. Therefore, second generation fans are always connected to floodplains or channel areas.

Because rivers set the lower boundary for hillslopes throughout a watershed, incision along the channel network dictates the local rate of base level fall experienced by each hillslope (Kirby and Whipple, 2012). The Garona shows different incision rates along the study area, between 1.03 and 1.56 $mm\,yr^{-1}$ in the study area A, and between 0.68 and 1.17 $mm\,yr^{-1}$ in the study area B. Stange et al. (2014b) described this upper reach of the Garona as a bedrock river incised in the Palaeozoic basement, with several minor knickpoints where the river crosses major fault lines or lithological contacts. According to Kirby and Whipple (2012), river profile segmentation may develop as a consequence of changes in bedrock lithology, uplift rate and/or climate. The observed changes in incision rates can be related to this river profile segmentation. The obtained values for incision rates (between 0.68 and 1.56 $mm\,yr^{-1}$) are much higher than the uplift rates estimated by Ortuño et al. (2013), between 0.08 and 0.19 $mm\,yr^{-1}$. Hence, the entrenchment dynamics of the Garona River must be controlled by other factors apart from tectonics or isostatic rebound, for instance climate and material availability.

Incision is the phenomenon that seems to dominate nowadays in the Garona basin. Active alluvial fans and alluvial plains rework and redistribute the eroded material and export most of it out of Val d'Aran, as it happened during the 2013 flood. Material erodibility on the valley heads and steep slopes are the main factors that facilitate the entrenchment of lateral tributaries (CHEbro, 2008).

A similar postglacial evolution has been proposed in other former glaciated areas. Rosique (1997) studied the climatic implications of the recent Würm in the southern French Alps, showing that after the glaciers retreat there is an increase on torrential detritism, as well as a slope destabilisation process, followed by a vertical incision tendency of rivers during the Bølling-Allerød interstadial amelioration. The final stage is related to the development of large floodplains with deposition of fine material during low competence Holocene floods.

7.3 Present incision tendency

Channel evolution is the result of fluvial dynamics, so the effects of extraordinary events such as the flood on 18 June 2013 are highly dependent on the Garona River entrenchment tendency. However, flood events will locally produce different effects (e.g., lateral erosion and channel widening, incision and channel narrowing, accumulation). Erosion and accumulation areas are to a great extent related to slope changes of the Garona River and to confluences with tributaries.

Most entrenched stretches usually correspond to the steepest ones and entrenchment is less apparent where the slope is lower. Accumulation commonly occurs downstream the confluences with rivers with high sediment load, where the transported material is deposited due to the slope decrease. By and large, sediment load is higher in those streams at the left side of the Garona (e.g., Valarties and Nere) where extensive outcrops of glacial sediments are found in their catchments (ICGC [online], 18 July 2015). Accumulation also occurs along the Garona gentler stretches and overflow areas, where the flow speed is lower. In an entrenched fluvial stretch, lateral and vertical incision dynamics results in an increase of river depth and energy, so gravels can be easily transported. These gravels will be partly exported downstream or accumulated where energy decreases.

In the study area, erosive effects clearly dominate those related to overflows and/or accumulation. In fact, apart from a long-term erosive tendency (induced by tectonics, climate, geological structures and topography), extraordinary events induce episodic and relatively short-term entrenchment. Flood hydrodynamics obviously plays a role, as the flood tends to recover the channel space occupied by anthropogenic embankments. This is another factor explaining the total erosion. Thus, present indicators support the idea of a dominant entrenchment tendency and the 2013 flood effects reflect this hypothesis.

Flooded area corresponding to an event of 50-year return period has been mapped by the ACA (Civil Protection Map). If we compare the 2013 flood effects map presented in this study with the Tr = 50-year map carried out by the ACA, we realise that overflow points are actually minimum and the flooded area is significantly smaller (Fig. 15). This fact could be explained considering that the 2013 event, even if it was an extraordinary one, might not correspond to a 50-year return period flood, but it would represent a more frequent event (Tr < 50 years). On the other hand, assuming that the 2013 event corresponds to a Tr = 50-year one, the difference between the two maps could be explained by the predominance of erosive effects instead of overflow processes, partly due to the existence of channelization dykes confining the channel and inducing vertical incision. In this case, incision dynamics is reflected in the reduction of the flooded area extension. Map differences could also be explained as a combination of both factors.

Hence, the magnitude and importance of erosive effects need to be considered for flood hazard assessment and management.

7.4 Implications for management

Flood risk management has to consider, apart from the physical phenomenon, fluvial network behaviour and anthropogenic changes, in order to implement appropriate measures. According to Mazzorana et al. (2013), characterisation of several processes is needed for an adequate risk assessment, management and mitigation in mountainous regions, such as erosion and incision, slope changes, sediment budget, land use changes, obstructions, location of urban areas, etc. The continued long-term and long-scale erosion of the fluvial network induces changes on the flood magnitude (inundation energy and extension of overflow flooded areas) and frequency (return period of the events) (Macklin et al., 2013), so the erosive tendency needs to be considered for a good river management.

In the Aran valley, however, anthropogenic actions within the channel and land management have not taken into account this fluvial tendency, leading to erosion control to be a crucial problem. Moreover, in some cases anthropogenic actions enhance hydrodynamic effects and induce an even higher vertical incision rate. Since

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the second half of the 20th century, the Garona River dynamics has shown an acceleration of the vertical incision and a slight decrease of overflow phenomena (especially for not really severe floods), due to several actions like channelization. In fact, channelizations produce changes in discharge and channel morphology, inducing functional changes in the floodplain, as shown in the study carried out by Steiger et al. (1998) in the upper French part of the Garona River. In fact, these anthropogenic elements prevent overflow but increase the risk downstream, affecting floodplains at the end of channelized stretches, as occurred in Vielha during the 2013 event.

Hydraulic structures like dams and gauging stations have to consider the continued river erosion to prevent fluvial material from being eroded downstream from this engineering constructions. Besides, foundations of lateral dykes need to be deep enough, as vertical incision intensifies along channelized stretches because dykes avoid margin erosion (e.g., channelization dykes in Les). Bridges are one of the most vulnerable structures to erosion processes as they commonly reduce the channel section and pillars tend to be continuously eroded. Therefore, these engineering works should take into account both the river entrenchment and the local effects associated to the bridge itself. Moreover, all these hydraulic structures must have periodic monitoring and supervising controls in order to detect specific points affected by the continued fluvial erosion that may endanger its own stability. If these local incisions are not previously detected, incision effects during extraordinary flood events will probably be devastating.

The land use and management in valley bottoms should be exhaustively controlled, especially urbanisation in floodplain areas. These high risk areas should be devoted to agriculture, gardens, parks and uncovered leisure zones.

Finally, it is worth mentioning some of the undertaken actions after the event on 18 June 2013. The Ebro Hydrographic Confederation (CHE) carried out works to improve the river transport capacity, by giving a relatively constant width to the river channel (Moreno et al., 2013). Some post-event correction measures were identified during the field survey, noticing that they focused on repairing or reconstructing lateral channelization dykes (e.g., in Arties), repairing roads and hydroelectric dams (e.g., the C-28 road at the Salider alluvial fan, and the Arties dam), filling eroded zones (e.g., the Garona meander upstream from Vielha) and confining the Garona channel either with rock embankments (cemented or not cemented) or gravel and earth embankments. Nevertheless, where the channel was delimited by rock or earth embankments, it happens to be an ineffective measure, as the new channel width is almost the same as before the flood, so the river will tend to erode laterally or, where not possible, vertically. Besides, materials used for these confining measures are easily eroded and incorporated to the river, as in the gravel and earth embankments at the Vielha industrial park where up to 1 m of fluvial erosion was measured in less than a year.

8 Conclusions

The present work relates the geologic and geomorphologic context of Val d'Aran with current fluvial processes and bridges the gap between the long-term tendency and the short-term river response. In this way, the effects of flood events can be explained by the regional geomorphological evolution since, at least, the Miocene.

In the Aran valley, a mountain region affected by the last Upper Pleistocene glaciation, flash floods and torrential floods pose a hazardous risk, causing severe effects and damages. The last extraordinary event on 18 June 2013, produced several geomorphological effects, especially erosion along most of the Garona River length. Moreover, some accumulation areas, slope processes and alluvial fan activity were also recorded. However, erosive processes largely were the most significant ones, which can be explained by the river regaining its natural space (where in the last decades vulnerability and exposure increased due human occupation of flood prone areas, especially channel areas and floodplains) and/or by the generalised incisive tendency of the fluvial network. Several evidences at different time and space scales serve to assess the long-term fluvial entrenchment dynamics.

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Val d'Aran is located in the Pyrenean Axial Zone where recent and active tectonics influences drainage and fluvial dynamics. The post-orogenic exhumation and uplift (isostatic rebound) seems to induce river entrenchment. These tectonic evidences point out an incisive tendency since the Miocene.

During the last Upper Pleistocene glaciation, Val d'Aran was occupied by the ca. 70 km long Garona glacier, so alluvial deposits and landforms found at the valley bottom were formed during late-glacial and postglacial times. The postglacial geomorphological evolution is the result of several factors, among which climate, active tectonics and human impact are probably the most influential ones. The last glacial–interglacial transition gave rise to a period characterised by a powerful torrential activity, when high terraces and large alluvial fans were deposited. After this initial phase, as torrential detritism decreased, the fluvial network turned to an incisive tendency and the former geomorphological features were cut and smaller alluvial fans were formed in some confluences. Afterwards, fluvial network turned to be dominated by floodplain alluviation. Progressive erosion during the Holocene has shaped the landscape, with an estimated entrenchment rate between 0.68 and 1.56 mm yr^{-1} since deglaciation.

At present, the Garona River shows an erosive tendency. The 2013 flood event was characterised by mainly producing lateral and vertical erosion and, moreover, incision evidences were found in many anthropogenic hydraulic structures.

This case study clearly evidences that the geologic and geomorphologic setting controls river response. Thus, the long-term evolution of the area strongly influences the present river entrenchment dynamics, which poses a challenge for flood risk management.

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Table 1. Erosion values during the 2013 flood event along the two study areas.

	Study area A		Study area B	
Garona River margins	18 490 m	100 %	12 475 m	100 %
Eroded margins	8198 m	44.3 %	6236 m	46.3 %

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Table 2. Comparison between the flood prone area and the 2013 flood event accumulation and flooded areas, along the two study areas.

		Study area A		Study area B	
Flood prone area	Ancient channel	172 700 m^2	100 %	228 200 m^2	100 %
	Floodplain	672 400 m^2		1 153 900 m^2	
Accumulation areas		109 400 m^2	13 %	342 800 m^2	25 %
Flooded areas		367 100 m^2	43 %	483 400 m^2	35 %

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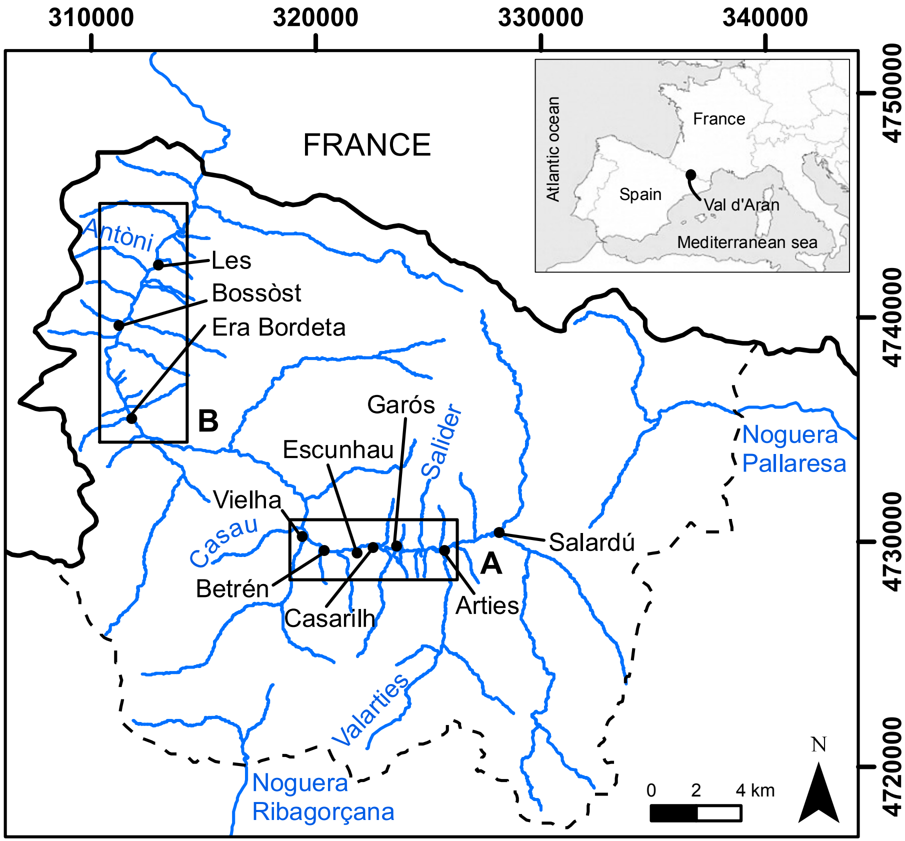

Figure 1. Location and sketch map of Val d'Aran with study areas A and B, main streams (in blue) and towns (in black).

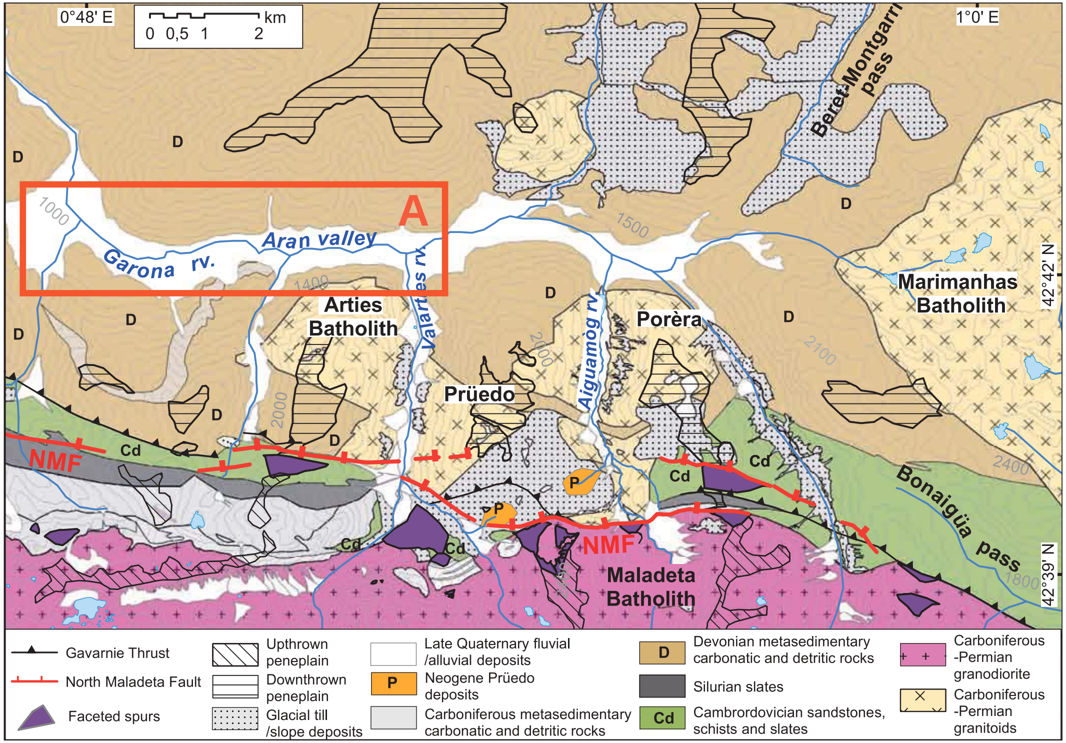

Figure 2. Geological map of the upper reach of the Garona River with the study area A in red. Planation surfaces and glacial deposits are also shown (Modified from Ortuño et al., 2013).

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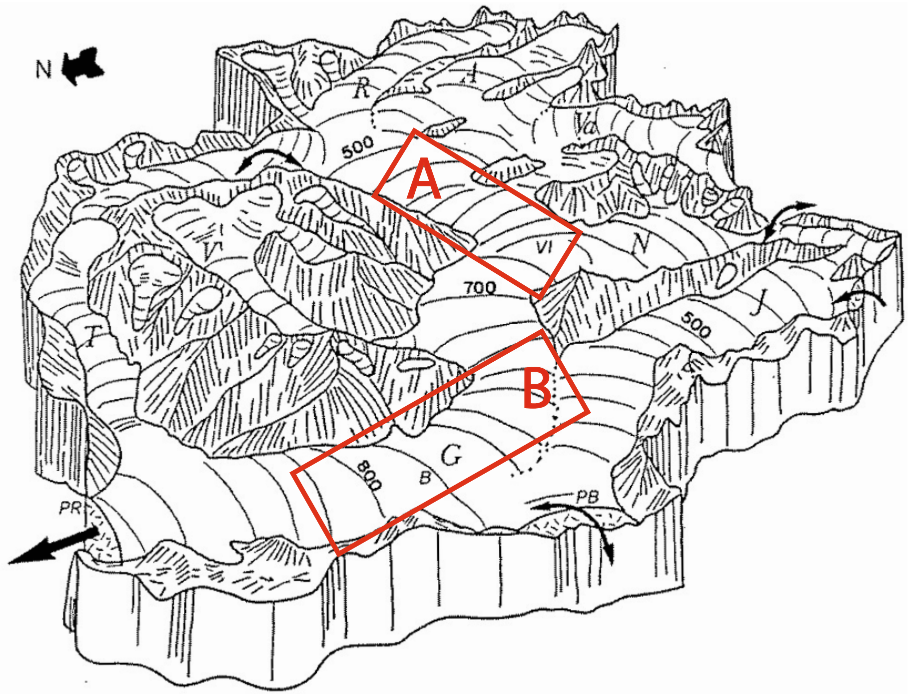

Figure 3. Reconstruction of the Upper Pleistocene glacier extension during the last glacial maximum with each study area in red. Numbers indicate the glacier thickness in meters (Bordonau, 1992; modified from Vilaplana et al., 1986).

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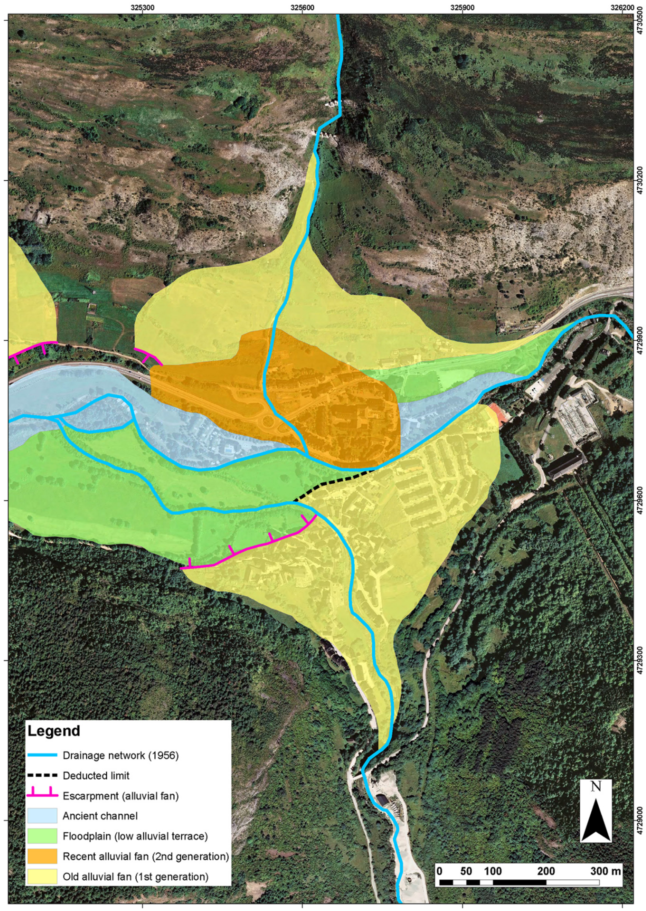

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Figure 4. Geomorphological map of the Arties area (in study area A), over the 25 cm resolution ortophoto from the ICGC. The tributary river (south) is the Valarties River. The map shows two generations of alluvial fans. The second generation alluvial fan is inserted in the previous one due to river entrenchment. Recent alluvial fan is connected to the functional or ancient channel area.

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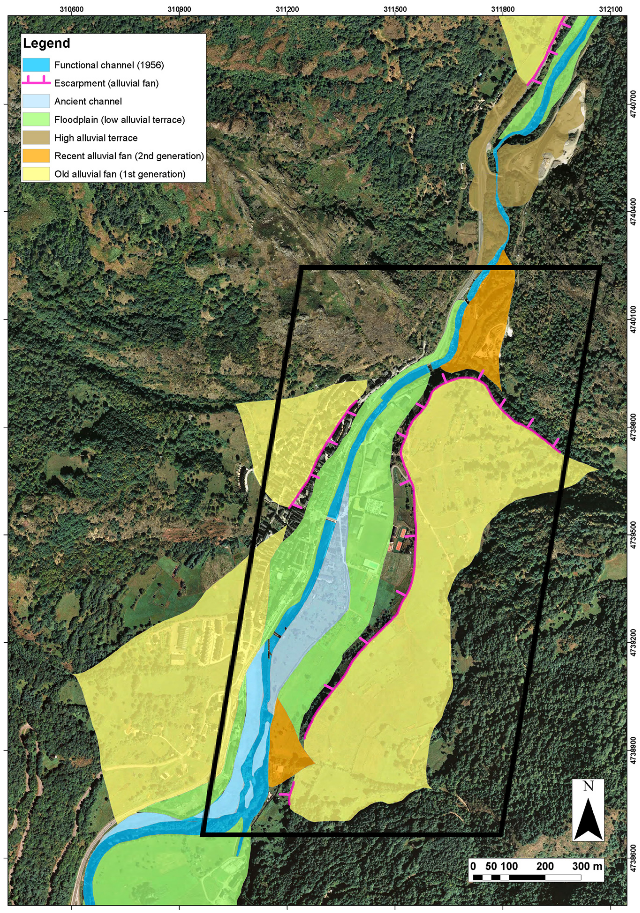

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Figure 5. Geomorphological map of the Bossòst area (in study area B), over the 25 cm resolution ortophoto from the ICGC. Two generations of alluvial fans and alluvial levels are shown in the map. First generation alluvial fans are usually incised in their distal part (except the one in the left bottom). Second generation ones are connected to channel areas. The black square frames the area shown in the Fig. 7.

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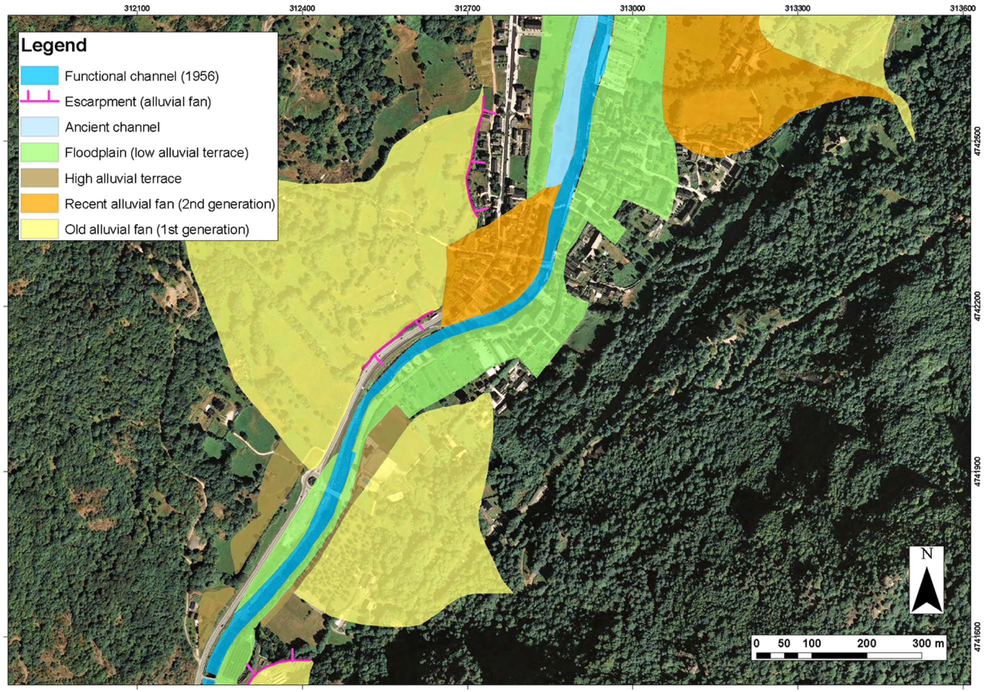

Figure 6. Geomorphological map of the Les area (in study area B), over the 25 cm resolution ortophoto from the ICGC. Two generations of alluvial fans and alluvial levels are shown in the map. Inactive alluvial fans from first generation are linked to high alluvial terraces or their distal part is eroded. Recent alluvial fans connect with the floodplain or the channel area.

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Figure 7. Recent alluvial fans emplaced in the distal part of ancient alluvial fans at Bossòst. The old alluvial fan shows a 15–20 m high escarpment related to the fluvial incision of the Garona River (photo Glòria Furdada, 17 January 2014).

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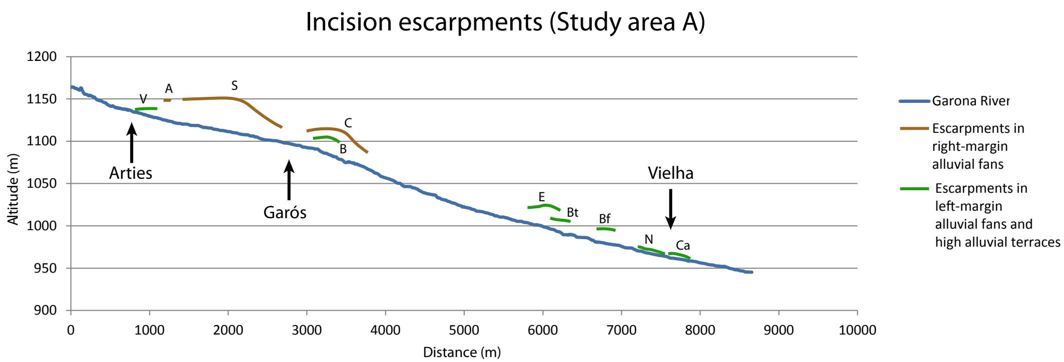

Figure 8. Topographic profile of the Garona River along the study area A with the height of the escarpments formed in the first generation alluvial fans and high terraces. Data show a differential entrenchment: clear entrenchment evidences are found in the upper and middle part of the Garona River, whereas no entrenchment indicators are detected in the lower part. V: Valarties alluvial fan; A: Artigues alluvial fan; S: Salider alluvial fan; B: Bargadera alluvial fan; C: Cal alluvial fan; E: Escunhau alluvial fan; Bt: Betrén high alluvial terrace; Bf: Betrén alluvial fan; N: Nere alluvial fan; Ca: Casau alluvial fan.

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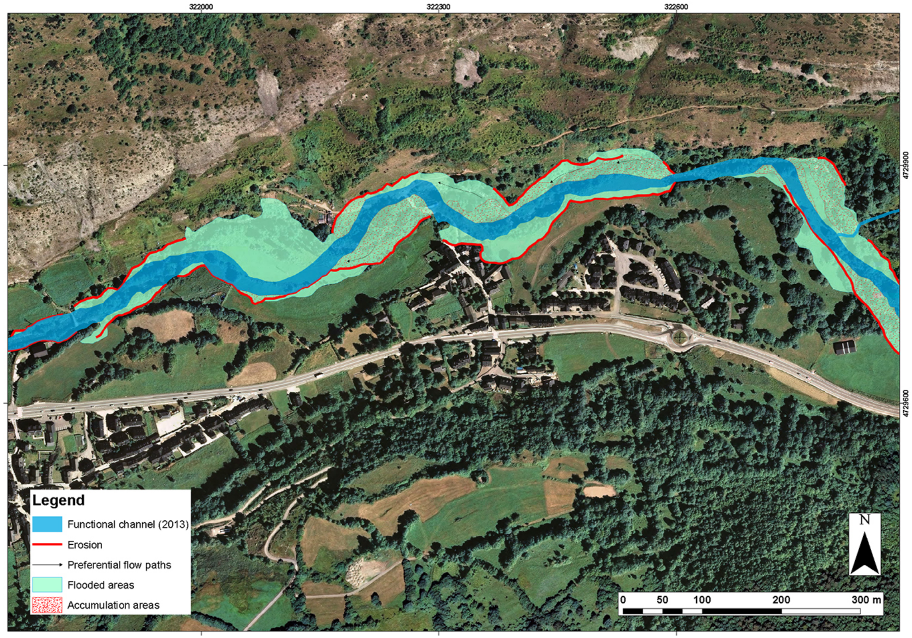

Figure 9. 2013 flood effects map of the Casarilh area (in study area A), over the 25 cm resolution ortophoto from the ICGC. Lateral erosion and channel widening were recorded almost all along this area.

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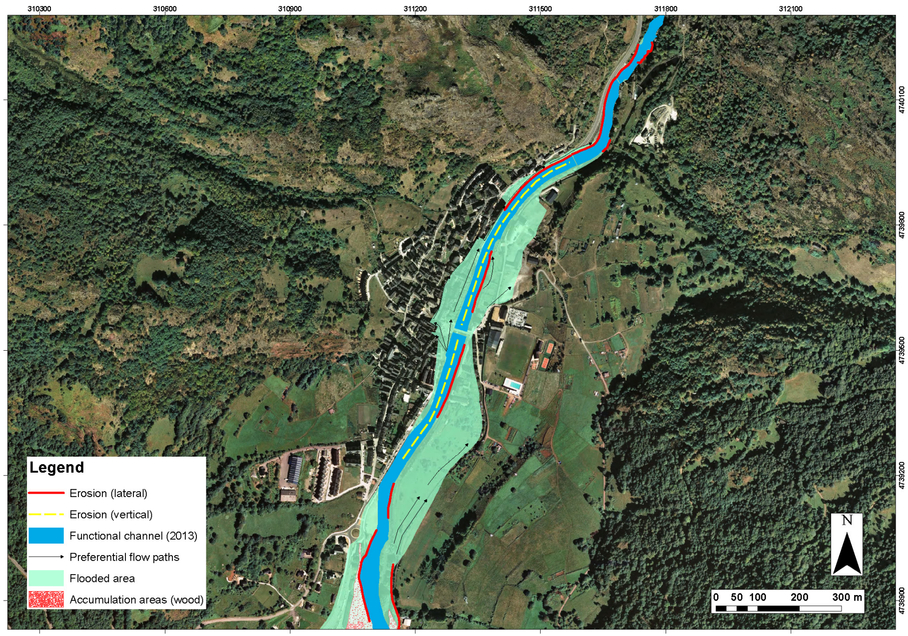

Figure 10. 2013 flood effects map of the Bossòst area (in study area B), over the 25 cm resolution ortophoto from the ICGC. The river is channelized along the town, showing lateral erosion and vertical incision.

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Figure 11. Erosion in the right side of the Garona River at Arties. The building was damaged during the 2013 event and it had to be reconstructed (photo Glòria Furdada, 17 January 2014).

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Figure 12. Collapse of a channelization dyke at Les due to vertical incision (photo Glòria Furdada, 15 January 2014).

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Figure 13. Vertical incision in a channelization at Les. Imbricated clasts below the scoured dyke prove that the Garona River entrenched into its channel bed deposits. The flow direction is indicated with a blue arrow (photo Glòria Furdada, 15 January 2014).

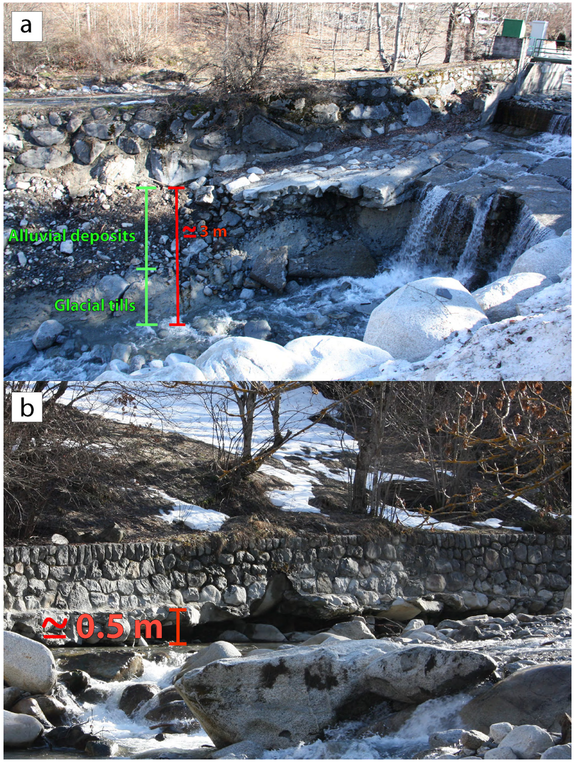

Figure 14. Erosion evidences in the Valarties River. **(a)** The 3.5 m incision downstream from the gauging station (partly related to local turbulences) allows the outcrop of fluvial and glacial deposits. **(b)** The incision is about 0.5 m below the channelization dyke upstream from the gauging station (photos Glòria Furdada, 17 January 2014).

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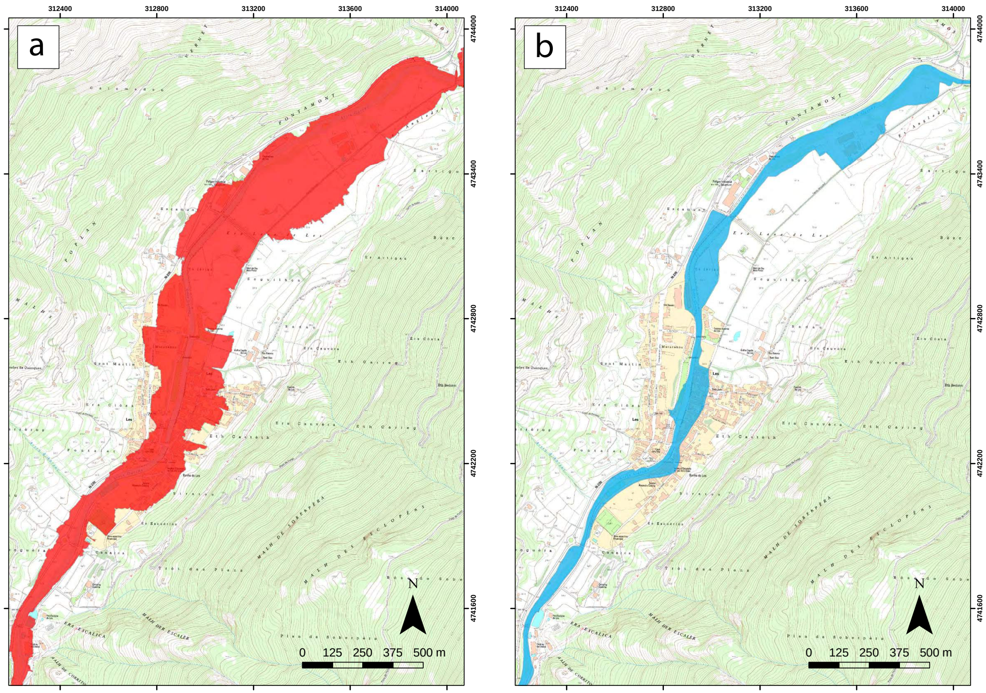

Figure 15. Flooded areas at Les, over the 1 : 5000 topographic map from the ICGC. **(a)** Flooded area corresponding to 50 years return period events according to ACA. **(b)** Flooded area during the 2013 event.

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