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

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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 EUR100 million. Few studies have related flood events to the geologic, tectonic and geomorphologic context. This study deals with both short- and long-term processes by studying the upper reach of the Garona River on different timescales and space scales. There has been a clear entrenchment tendency of the drainage network since the Miocene. Post-orogenic exhumation and uplift of the Axial Pyrenees determines the recent and active tectonics of the area and leads to fluvial incision. The last Upper Pleistocene glaciation affected Val d'Aran and gave rise to a destabilization period during the glacial–interglacial transition, marked by a postglacial incision tendency. Mean entrenchment rates between 0.68 and 1.56 $\mathrm{mm\,yr^{-1}}$ since deglaciation have been estimated. The assessment of the 2013 flood, characterized by the predominance of vertical incision and bank erosion, suggests that the long-term tendency of the fluvial system is reflected in short-term processes. The study of the geologic and geomorphologic evolution, combined with the analysis of this 30–50-year return period flood event, helps to improve flood risk management by providing contextual information that can constrain predictions and help guide choices and decisions. In fact, the millennial entrenchment tendency is shown at the human scale, which is considered useful for river management, but could be imperceptible in detailed hydrodynamic and channel morphology studies that describe river dynamics mostly at the 10–15-year timescale.

1 Introduction

Floods are one of the most dangerous natural disasters worldwide as they produce severe socioeconomic, cultural, geomorphologic and environmental impacts, especially in urbanized areas (Jonkman, 2005; Barredo, 2007; Ashley and Ashley, 2008; Gaume et al., 2009). In Catalonia (Spain), according to the National Plan for Flood Risk (Protección Civil, 2011), floods constitute the most frequent and damaging hydrogeological risk.

The importance of timescales when studying fluvial systems and their evolution has been highlighted in literature (Harvey, 2002). Some previous works exclusively deal with long-term geomorphologic and tectonic processes that determine landscape evolution, but are imperceptible in those timescales used for river management (Dietrich et al., 2003; Oskin and Burbank, 2005; Bishop, 2007; Kirby and Whipple, 2012). Other research lines focus on flood events, present processes and landforms, or short-term river morphologic evolution (Baker and Pickup, 1987; Beven, 1987; Montgomery and Buffington, 1997; Lenzi, 2001; Mao et al., 2009; Zanon et al., 2010). Many others deal with river corridor management, which has evolved from a product-oriented engineering approach to a dynamic multi-objective management approach (Gregory et al., 2008). The need of a fluvial geomorphological assessment for adequate river engineering and management has been addressed in previous works (Schumm, 1977; Schumm et al., 1984; Thorne et al., 1997; Kondolf and Piégay, 2003), and methodological frameworks for hydromorphological analysis with applications for risk mitigation have been developed in the last decade (Rinaldi et al., 2014; Belletti et al., 2015; Gurnell et al., 2015). Belletti et al. (2015) present a review of the existing main hydromor-

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phological assessment methods, showing their strengths, limitations, gaps and need for further development. According to Belletti et al. (2015), understanding evolutionary trajectories and past changes is an important component when assessing river conditions using geomorphologically based robust approaches. However, one of the main limitations is the difficulty to assess the temporal component. Lastly, there are also many studies giving importance to the anthropic actions that produce changes in the river evolution on a year to decennial timescale (Gregory et al., 2008 and references therein). An approach on different timescales and space scales allows a better understanding of the basin and river response.

The present study focuses on the flood risk in Val d'Aran (Central Pyrenees, Spain), where torrential events show a high recurrence. The flood that occurred in the summer of 2013 produced significant geomorphic effects and economic losses all along the Garona River (Garonne in French) in Val d'Aran (Geological Institute of Catalonia, IGC, 2013; Pineda et al., 2013; CHE, 2014; García-Silvestre, 2014; Victoriano, 2014), but the interpretation of the river dynamics still requires further research.

The objectives of this study are to analyse the long-term dynamics of the Garona River in order to understand short-term processes, and highlight how the regional geologic and geomorphologic context helps to understand present river response and future evolution in our case study. The present study on different timescales could be incorporated into an integrated methodological framework for river corridor assessment and management, such as the IDRAIM system (Rinaldi et al., 2014), as the long-term tendency has implications for flood risk management.

2 Study area

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

Val d'Aran (Catalonia, Spain) is located on 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. (Cartographic Institute of Catalonia, ICC, 1994). Population is mainly settled along the valley bottoms (9993 inhabitants; IDESCAT, 2014). Urban settlements have only increased along valley bottoms during the last decades and land use has not changed significantly since 1946 in this mountainous area, so its influence in fluvial evolution and discharge values is almost absent. Due to its northern orientation, the area is characterized by an alpine Atlantic climate, with high humidity, 6–10 °C mean annual temperature, 900–1100 mm mean annual precipitation and a balanced seasonal rainfall pattern (Water Agency of Catalonia, ACA, 2015). Maximum precipitation in terms of intensity and frequency is recorded in spring and autumn, whereas snowfall precipitation occurs mainly in winter.

The Garonne River drains into the Atlantic Ocean in an area of 52 000 km^2 along ca. 600 km (Stange et al., 2014a). However, Val d'Aran corresponds to a small headwater area of 620 km^2, where the Garona River flows along 45 km without large dams, showing a well-developed drainage network, significant gradients (reaching 2.5 % in some stretches of the main river and higher than 20 % in tributary streams) and steep slopes. The uppermost zones of fluvial systems are characterized to be the production or sediment-source area, from which sediment is removed and delivered downstream, giving rise to the long-term erosional evolution of the landscape (Schumm, 1977; Rinaldi et al., 2014). Although sediment is eroded, stored, transported and deposited along the entire fluvial system, one process is usually dominant in each part. The main expected phenomenon in our study zone is, therefore, erosion.

In order to study the Garona catchment, and although the 2013 flood produced much damage along most of the major river length, we selected two stretches (Fig. 1) representative of 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 stretch between the Arties and Vielha municipalities (approximately 8.3 km long), including Garós, Casarilh, Escunhau and Betrén. Study area B, ca. 9 km downstream of study area A, includes the river stretch along Era Bordeta, Bossòst and Les (approximately 12 km long). These two study areas will provide relevant and representative information about the Garona River dynamics in Val d'Aran.

2.1 Flood hazard and assessment of the 2013 event

Val d'Aran is susceptible to suffering mountainous torrential flood events and it is classified as a high flood risk area (ACA, 2015). Flood events are documented to have occurred in 1875, 1897, 1907, 1937, 1963 (August and November), 1982 and 2013 (Piris-Casanovas, 2013; García-Silvestre, 2014; Lang and Coeur, 2014). The available hydrometeorological data of the historical events, their geomorphic effects and a comparison with the projected 25- and 100-year return period (RP) floods are collected in Table 1.

The last event was a devastating flash flood in the summer of 2013 (18 June). Several geomorphic effects (lateral and vertical erosion, debris accumulation, shallow landslides and torrential flows, and reactivation of some alluvial fans) and damage to anthropogenic facilities (e.g. buildings, campsites, roads, bridges, dams, hydroelectric plants, channelization dykes) were recorded throughout the Garona River and some of its tributaries (IGC, 2013). Even if there were no fatalities, the total economic losses reached up to EUR 100 million (Corporació Catalana de Mitjans, 2014). Meteorological and hydrological causes of the 18 June 2013 flood in Val d'Aran

Table 1. Data compilation of major historic floods in Val d'Aran (except for the 1897 and the November 1963 floods, due to a lack of data), the 2013 flood and the calculated 25- and 100-year return period floods. All data are related to the villages where they were collected or observed, and ordered downstream.

	22–24 Jun 1875		22–25 Oct 1907	24 Oct 1937		03 Aug 1963			06–08 Sep 1982			18 Jun 2013	RP = 25 years	RP = 100 years
	Q ($m^3 s^{-1}$)	Effects: the Garona River overflowed all along the valley [f,l]	Rainfall (mm)	Q ($m^3 s^{-1}$) Highest recorded peak discharge [i]	Effects: road erosion and scouring (2 m deep and 150 m long; Vielha – France).	Q ($m^3 s^{-1}$)	Rainfall: local, intense summer storm on saturated soils (high rainfall in July)[a]	Effects: road erosion (10 m long; Salardú – Vielha)[a]	Rainfall (mm): (200 mm in 3 days)[g]	Q ($m^3 s^{-1}$)	Effects: almost the entire valley affected[d]; erosion (road: local erosions along 30 km)[k].	Q ($m^3 s^{-1}$) (40 % Q from snow melting)[c]	Q ($m^3 s^{-1}$)	Q ($m^3 s^{-1}$)
Salardú												92–130 (RP < 50)[c]	124[l]	229[l]
Arties						325 in the Valarties River[j]		Valarties River overflowed; erosion and scouring in the Valarties and Garona rivers[a]; medieval bridge destruction; 2 m accum. in the Valarties alluvial fan[a].	112[k]		The Valarties River overflowed; bridge clogging[d].	233 just downstream from the Arties dam[c] 146–170 (RP < 50)[c]	134–174[l]	246–316[l]
Garós–Casarilh								Garós: Bargadera bridge destruction[a]						
Vielha			300[k]	80 in the Nere River[b]	The Nere River overflowed; 1.5 m accum. at the Nere alluvial fan (Vielha: Llibertat street) [b]; sediment input from the works in the Alfonso XIII tunnel, at the Nere River headwaters[b]				170[k]		The Nere River: clogging at the confluence in Vielha and up to 1 m accum.[d]; the Joeu River overflowed[d]	230 (RP < 50)[c]	200[l]	368[l]
Aubert												245–260 (RP < 50) [c,g]	204[l]	380[l]
Bossòst				360[i]	Pont Vell bridge destruction [b]				162[k]			280–339 (RP < 50) [c,g,i]	257[l]	380[l]
Les				400[k]	La Lana bridge destruction [b]									
Pont de Rei		Bridge destruction (clogging)[m]		700[e]		250[e]				250[c]				
Saint Béat (France)	400[j]													

Source: [a] Aran Culturau (2013); [b] Archiu Generau d'Aran (1937); [c] CHE (2014); [d] Geli (2007) and Saèz (2007); [e] La Vanguardia (1963); [f] Lang and Coeur (2014); [g] LOOP, last access: 16 December 2015; [h] Moreno et al. (2013); [i] Pineda et al. (2013); [j] Pino et al. (2016); [k] Protección Civil (1988); [l] SNCZI (2011); [m] Trutat (1898).

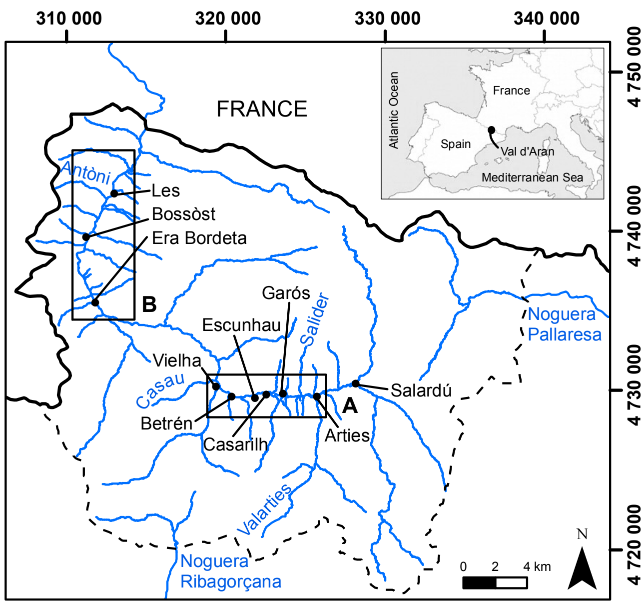

Figure 1. Location and sketch map of Val d'Aran with study areas A and B, main streams (in blue) and towns (in black).

have been accurately studied. Heavy rainfall (124.7 mm in 48 h in Vielha, 100 mm of them in 24 h) and fast snow melting (51 hm^3 in 10 days, 40 % of the flood discharge) were regarded as the triggering factors (Pineda et al., 2013; CHE, 2014). Gauging stations were destroyed, so real-time discharge data were not available. Peak discharges were then estimated from flood evidence and/or hydraulic modelling (CHE, 2014). Pineda et al. (2013) and CHE (2014) classify the flood as a RP < 50-year event. We estimate that the 2013 event was a 30–50-year medium-magnitude flood (Table 1) that shaped the channel morphology, so it was not an extreme one.

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 fold and thrust system almost parallel to the mountain chain. According to Fontboté (1991), geological materials of the Pyrenees can be grouped into 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 (Fig. 2). Recent neotectonic studies in the Pyrenees (Lacan and Ortuño, 2012; Ortuño et al., 2013) have identified zones indicating a continued uplift related to isostatic processes, and proved the existence of active tectonics.

The present landscape of the Pyrenees mostly results from the Upper Pleistocene last glacial period, with scarce and poorly preserved evidence of previous glaciations. Glacial cirques and valleys were excavated into Neogene (Upper Oligocene–Lower Miocene) high planation surfaces whose remnants are clearly visible in the summit areas above 2000 m a.s.l. (Mianes, 1955; Ortuño et al., 2013). 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 study area, formed by Palaeozoic basement rocks, constitutes the upper catchment of the Garona River and one of the main accumulation zones of the Upper Pleistocene former 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 (Fig. 3) (Bordonau, 1992). A time lag between the maximum ice extent in the Pyrenees (> 40 ka) recorded during MIS 4, and the global Last Glacial Maximum (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., 2016) has been proved for the Pyrenean glaciers. In the Garona valley, the glaciolacustrine and till deposits at the base of the Barbazan Lake fill sequence, about 30 km downstream of Les, have yielded an age of 31.16 ± 1.7 ka BP (32.037 to 39.407 ka cal BP), showing the presence of a glacier on that site until 26.6 ± 0.46 ka BP (29.786 to 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. Following the glacial maximum, only the youngest deglaciation phases, still undated in Val d'Aran, can be recognized by the presence of well-preserved lateral and terminal moraines corresponding to small valley and cirque glaciers. During the Holocene, geomorphological processes like those active at present prevailed in Val d'Aran.

Hence, the geomorphological features of the study area are indicative of the Garona pre-Quaternary and Quaternary evolution, mainly characterized by erosive processes and a progressive fluvial network entrenchment resulting from fluvial–torrential dynamics, giving way to alluvial fans, alluvial terraces and floodplains on deeply incised valleys.

4 Methods

The starting point of this work is the preliminary study done by the IGC in 2013. We used the geomorphological method to produce 1 : 5000 maps using GIS software and online WMS geoservices from the Cartographic and Geological In-

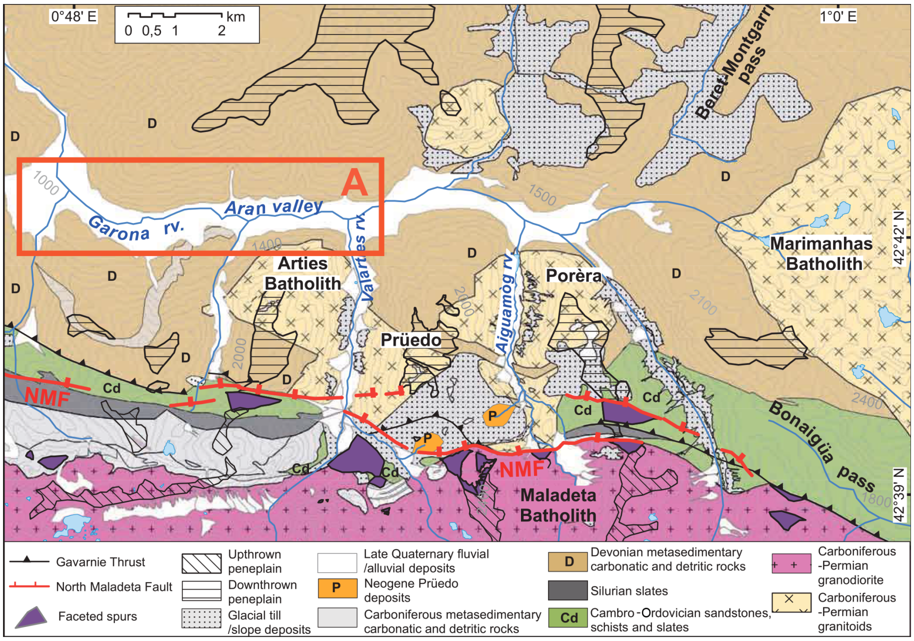

Figure 2. Geological map of the upper reach of the Garona River with study area A in red. Planation surfaces and glacial deposits are also shown (modified from Ortuño et al., 2013).

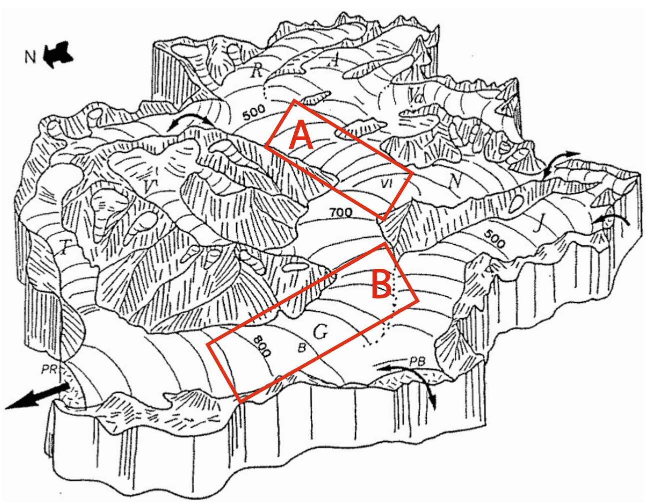

Figure 3. Reconstruction of the Upper Pleistocene maximum ice extent, with each study area in red. Numbers indicate the glacier thickness in metres (Bordonau, 1992; modified from Vilaplana et al., 1986).

stitute of Catalonia (ICGC, 2015). A preliminary geomorphological map of the area was done based on the photointerpretation of stereo-pair aerial images of the 1956–1957 American flight. This map was especially useful to recognize the main natural landforms, with little or no anthropization, which reflect the fluvial–torrential dynamics. A map of the flood effects was obtained by comparing the orthophotos of 2012 and 2013 (post-event) from the ICGC (2015).

Field surveys focussed on the verification of the preliminary maps, observation of the flood effects in situ, data collection of erosion and entrenchment indicators, identification of conflictive spots along the Garona River and observation of the post-flood defence measures. By integrating all the collected information, we obtained the definitive geomorphological and flood effect maps.

The dynamics of the Garona River was studied through the specific analysis of the identified entrenchment indicators, both long-term (geomorphological features) and short-term (flood effects and field observations). Entrenchment rates were also estimated. Transversal and longitudinal profiles allowed us to relate the flood effects to the long-term tendency of the drainage network. The data for these topographic sections were extracted from the 5 m digital elevation model of 2012 (ICGC, 2015).

5 Long-term dynamics of the Garona River

Previous studies by Victoriano (2014) and García-Silvestre (2014) showed evidence of an incision tendency of the Garona River in the Arties–Vielha and the Era Bordeta–Les fluvial stretches. In order to understand the natural river evolution, we identified, mapped and analysed the main fluvial, torrential and alluvial geomorphological features in the bottom of the Garona valley and the lower part of the main tributaries along the selected study areas. Figure 4 shows an example of the geomorphological mapping.

Concerning the main drainage network, in study area A, the Garona River is 8.3 km long and the mean gradient is

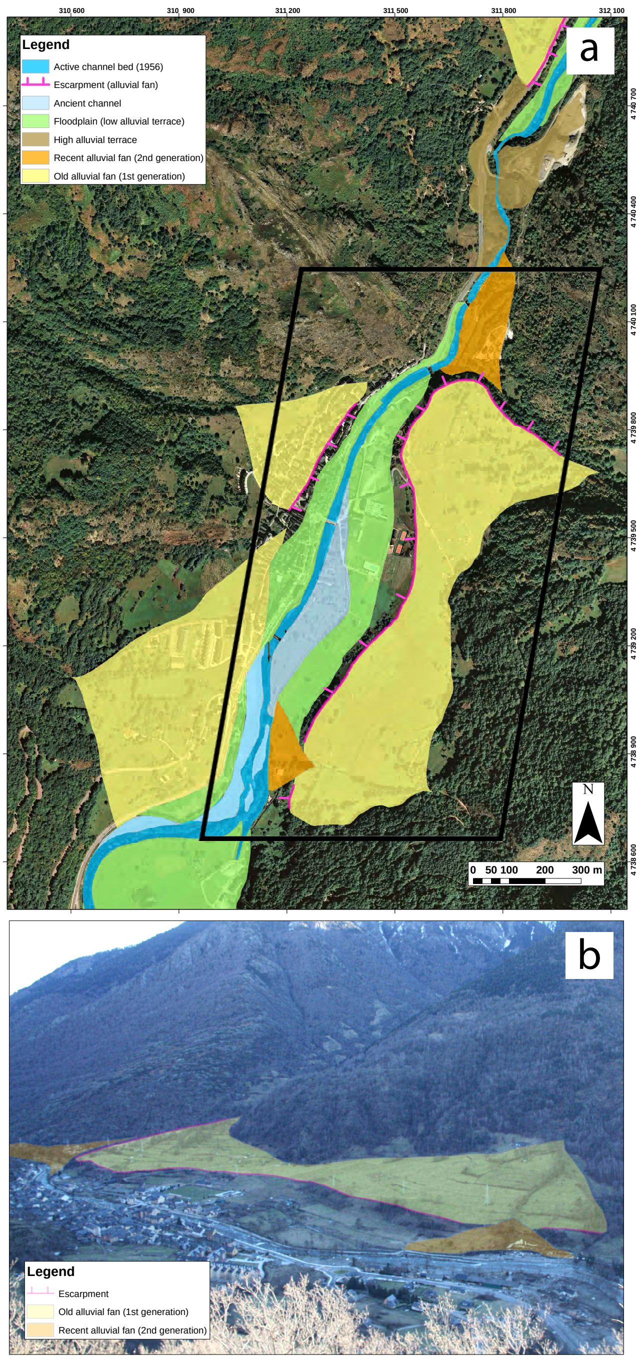

Figure 4. (a) The geomorphological map of the Bossòst area (in study area B), over the 25 cm resolution orthophoto (ICGC, 2015): there are two generations of alluvial fans and alluvial levels. The black square frames the area shown in **(b)**. **(b)** Recent alluvial fans are emplaced in the distal part of ancient ones, which show a 15–20 m high escarpment related to the incision of the Garona River (photo Glòria Furdada, January 2014).

2.5 %. In study area B, which is 12 km long, the mean gradient is 1.6 %. Nonetheless, the gradient is not uniform all along the studied stretches (Fig. 5). Anyway, the channel's present morphology is anthropogenically modified especially in urbanized areas, where the river is confined by channelization dykes or rock embankments.

Ancient channel areas were distinguished, which are part of the natural river channel system where water flows quite often or used to flow in the past (in some cases before channelling). They are flat areas 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.

There are two levels of alluvial terraces. The low level of alluvial deposits (3–10 m high) corresponds to the recent Holocene floodplain located discontinuously along both sides of the river and generally linked to the main channel or to ancient channel areas (Fig. 4). High alluvial terraces (10–20 m high), however, were formed during the last glacial–interglacial transition or even the Holocene. As the river entrenched, the ancient floodplains or valley trains (the present high terraces) became inactive and were substituted by new floodplains (the present low terraces). These two alluvial levels are part of the same postglacial terrace system formed after the retreat of the last Pleistocene glacier. In study area A, only two patches were found, the first one upstream of Betrén and the second one in Casarilh and Escunhau. The latter was recognized in the 1956 aerial photographs, but it was not identified in the field, most likely due to degradation and anthropization. In study area B, however, several terrace patches can be found, especially between Bossòst and Les (Fig. 4).

Two generations of alluvial fans were identified (Fig. 4). The smaller and more recent alluvial fans are emplaced in the distal part of the older and larger ones. This is the result of a change in the channel position due to river entrenchment, but the decrease of the sediment load from tributaries also affects in this process (see Sect. 7.2). In the upper and middle parts of study area A and in study area B, 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. In these cases, second-generation fans tend to be connected to channel areas or floodplains. In some cases, the two generations of alluvial fans were not identified, especially in the lower part of study area A (i.e. Vielha) and in the Valarties alluvial fan (i.e. Arties). These large alluvial fans without second-generation emplaced fans are generally linked to the channel or the floodplain.

Some of the alluvial fans and high terraces show decametric erosion escarpments related to fluvial incision. Old alluvial fans are cut in their distal part, showing a 15–35 m high escarpment. The height of the escarpment in the high terraces is 10–20 m, being higher in study area A. High alluvial terraces are the most significant geomorphological indicators in order to estimate the river entrenchment rate, since the incision in alluvial fans is influenced by their particular size and shape, as well as the location and evolution of the Garona channel. In study area A, the high terrace at Betrén indicates a fluvial incision of 15–20 m. These terraces formed

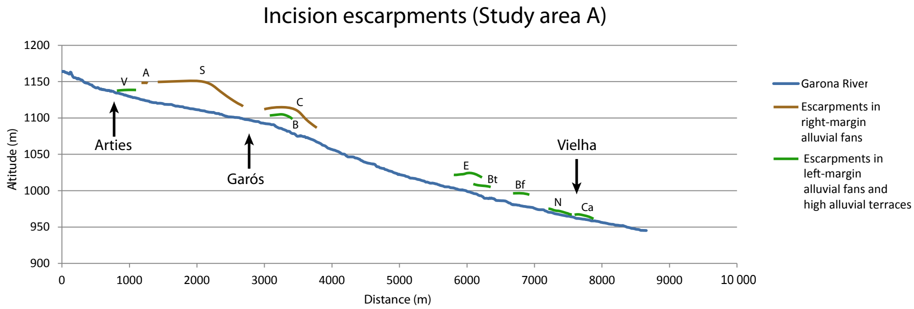

Figure 5. Topographic profile of the Garona River along study area A, with the height of the escarpments formed in the first-generation alluvial fans and high terraces. Data show a differential entrenchment: clear entrenchment evidence is found in the upper and middle parts of the Garona River, whereas 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.

shortly after the glacier retreat. The Garona glacier retreated from Barbazan, about 53 km downstream of 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 Val d'Aran but, according to ages obtained in the contiguous southern Noguera Ribagorçana glacial basin (Pallàs et al., 2006), the Garona glacier would have retreated upstream of Betrén between 14.6 and 12.8 ka (see Sect. 7.2). Assuming a constant entrenchment, in study area A, the approximate mean entrenchment rate of the Garona River is between 1.03 and 1.56 mm yr^{-1}. In study area B, 10–15 m high alluvial terraces are found upstream of Les, yielding an average entrenchment rate between 0.68 and 1.17 mm yr^{-1}.

The river is entrenched into the Palaeozoic bedrock in some sites, indicating a very high fluvial erosive power. For example, at Betrén (study area A), the river eroded all the alluvial fan deposits reaching the Palaeozoic basement, and continued entrenching into the slates and schists, generating an up to 20 m high escarpment.

The magnitude of vertical erosion data does not show a uniform spatial distribution. This differential entrenchment is reflected in the incised geomorphological features. The highest incisions are found in study area A, so we analysed escarpment values there (Fig. 5). 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 left side of the Garona River, values are lower (e.g. 15 m in the Betrén alluvial fan). In the lower part, the alluvial fans are not eroded. Nonetheless, 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. The inactivity of the first generation of alluvial fans and the formation of the second-generation ones can be explained both by the river entrenchment and the lack of sediment load to keep them active. In other cases, alluvial fans from the first generation are linked to the channel area or to the present alluvial plain, which can be explained by a higher sediment input than the

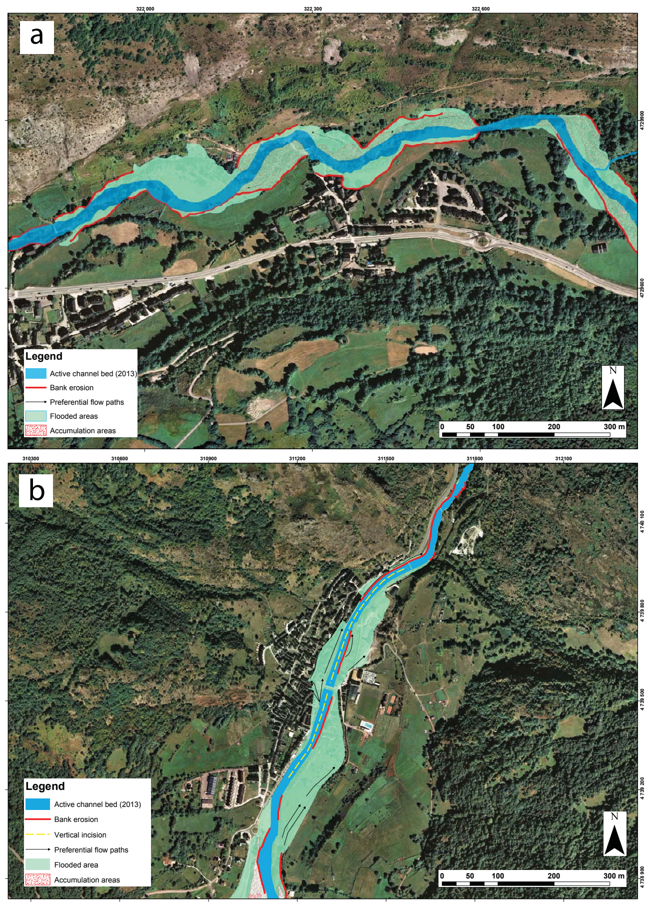

Figure 6. 2013 flood effects map over the 25 cm resolution orthophoto (ICGC, 2015). **(a)** Casarilh (in study area A): bank erosion and channel widening were recorded almost all along this area. **(b)** Bossòst (in study area B): the river is channelized along the town, showing bank erosion and vertical incision.

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 %

Figure 7. Effects of the 2013 flood event along the Garona River (photos Glòria Furdada, January 2014). **(a)** A damaged building at Arties by bank erosion that had to be reconstructed. **(b)** Collapse of a channelization dyke at Les due to vertical incision. **(c)** Vertical incision in a channelization at Les (the blue arrow indicates flow direction); imbricated clasts below the scoured dyke prove that the Garona River entrenched into its channel bed.

local entrenchment rate. Therefore, more exhaustive studies would be necessary to determine the causes of the differential incision.

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 incisive dynamics is reflected in present fluvial processes and flood hazard.

6.1 2013 flood effects

The origin and type of the effects are diverse, but they occurred in areas where flood hazard was known and foreseeable (Oller et al., 2013). We identified, mapped and analysed the main flood effects in order to know the present tendency of the fluvial system during flood events. Figure 6 is an example of the 2013 flood maps.

The course of the Garona River was modified during the event, both by channel modification (bank erosion and widening along almost all the river length, but also deepening in some stretches) and avulsion (e.g. downstream of Arties in study area A, and the meander at Era Bordeta in study area B).

Fluvial erosion was one of the most devastating effects causing severe damage in urbanized areas, especially in Arties (Fig. 7a), Bossòst and Les, where part of the dykes collapsed 2 days after the 2013 flood peak due to the loss of basal support (Fig. 7b). We considered the Garona River along the two study areas and the lower stretch of the Valarties River. 44.3 % (8198 m) and 46.3 % (6236 m) of study areas A and B recorded bank erosion, respectively, reflecting the significant magnitude of erosive processes. Moreover, these are minimum values because in some stretches, riverbank trees made it difficult to identify the erosion in the orthophotos, and some places were not accessible during the field survey. Erosion escarpments are generally not more than 1 m high, although they can be higher in some cases.

In terms of accumulation areas, a small part of the flood-prone area (ancient channel and floodplain) was covered by muds, sands, gravels, cobbles and/or wood, in fact, 13 and 25 % of study areas A and B, respectively (Table 2). This phenomenon occurs where slope decreases and/or in confluence areas. Two extensive accumulation areas were identified: the Era Yerla campsite downstream of Arties (where the Valarties tributary river joins the Garona) and the Padro Verde campsite in Era Bordeta. At these two sites, the deposited materials occupied about 55 000 m^2 (50 % of the total accumulation area in study area A) and 80 000 m^2 (23 % of the total accumulation area in study area B), and thicknesses of up to 2 and 1.5 m were measured, respectively.

Reconstruction of the flooded area and preferential flow paths was based on the analysis of the ICGC (2015) flood orthophotos, data from the IGC (2013) preliminary study, post-flood field surveys, geomorphological mapping and information provided by witnesses. Main flooded areas were recorded at Arties, the Vielha industrial park, Bossòst and Les. Flooding can be related to overflow or river widening by bank erosion. The estimated flooded area is about 367 100 m^2 in study area A (43 % of the total flood-prone area), and about

483 400 m^2 (35 % of the total flood-prone area) in study area B (Table 2).

Debris flows occurred in some tributary catchments, increasing the sediment load of the stream and leading to fan reactivation and deposition. Downstream of Arties (study area A) we identified the reactivation of the distal part of the Salider second-generation alluvial fan. The active part occupied about 1700 m^2, which corresponds to 3.5 % of its total area. 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; Table 1).

6.2 Erosion and entrenchment indicators analysis

In addition to the bank erosion and other flood effects, field observations in anthropogenic structures allowed us to identify some features that indicate the predominance of incisive processes.

Vertical incision is recorded below bridges and channelization dykes. The river has progressively eroded below the foundations of lateral dykes along channelized stretches. The stretch along Les shows the best example of this type of vertical incision (Fig. 7c). Erosion below bridge pillars was identified in Garós, where the river had incised almost 2 m since it was built, eroding the concrete and even 1.5 m of fluvial materials, so new foundations had to be reconstructed.

Gauging stations and dams are hydraulic structures where the river bed is not erodible, favouring erosion downstream of them, either by turbulent flow or hungry water erosion. However, in some cases, incision can also be observed upstream, even if the magnitude tends to be lower. Immediately downstream of the Valarties gauging station (Fig. 8a), a 3 m deep erosion was measured, showing a thin outcrop of alluvial and glacial deposits beneath the fluvial sediments. Incisions were also identified upstream (Fig. 8b), where the erosion cannot be explained by local turbulence. At the Arties dam, incisions between 0.4 and 1 m deep have been formed since it was built in 1948.

Although erosion in engineering 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

The present study proves that the Garona River shows evidence of a clear entrenchment tendency at least since the end of the last glacial period. Other regional studies confirm that this tendency can be recognized over different timescales, in fact, since the Miocene. The long-term erosional landscape evolution, as well as the analysed present processes, have implications for flood risk assessment, and can be integrated in methodological frameworks for river management.

7.1 Active tectonics and entrenchment

The Pyrenees is a mountain range 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), controlled by vertical maximum stresses, and the Low Chain, where horizontal maximum stresses seem to be dominant. They consider the Pyrenees as an active mountain belt, and affirm that in addition to the topographic gradient, other factors such as successive glaciations and periglacial weathering accentuated the erosion in the High Chain, which probably resulted in a differential uplift by isostatic compensation.

The important erosive phase in the High Chain after the Alpine orogeny compressive period 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 Late Miocene Prüedo lacustrine deposits, at about 3 km southeast of 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 (Late Miocene). This study also notes that a 2–3 km thick material removal has occurred in the last 10 Ma. The exhumation, related to the regional uplift and the activity of the North Maladeta Fault, 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 regularization processes (Turu Michels and Peña Monné, 2006).

Stange et al. (2014a) simulate stream profile development under potential scenarios (climate change, tectonic and isostatic uplift and lithological contrasts) in the Ebro foreland basin, including tributaries whose headwaters are in the Central Pyrenees (e.g. the Noguera Ribagorçana River, south of 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, which gradually increases towards the Pyrenees crest zone where the largest sediment volumes are excavated. Thus, regional uplift also provides a mechanism 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. 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).

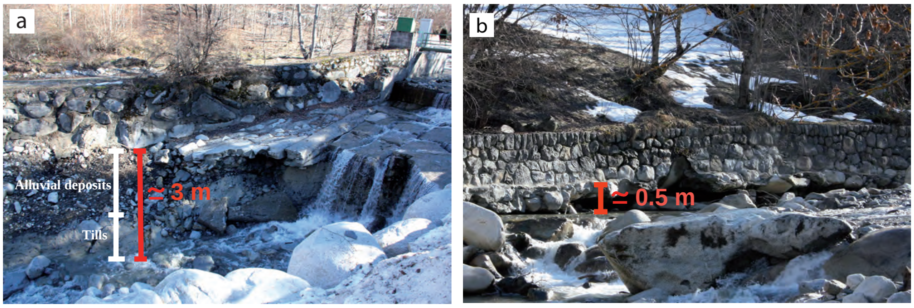

Figure 8. Erosion evidence in the Valarties River (photos Glòria Furdada, January 2014). **(a)** The 3.5 m incision downstream of the gauging station (partly related to local turbulence) allows the outcrop of fluvial and glacial deposits. **(b)** The incision is about 0.5 m below the channelization dyke upstream of the gauging station.

7.2 Postglacial geomorphological evolution

Many studies have focussed on the links between climate and fluvial system evolution. Traditional climatic theories related glacial periods to aggradation and interglacial periods to entrenchment, but many authors have proved that a number of factors also play an important role, such as sediment input, catchment morphometry, tectonics and anthropogenic actions (Vandenberghe, 2003).

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; Delmas, 2015). In Val d'Aran, 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 of the glacier head. Glacier retreat allowed the development of a fluvioglacial drainage network, while decompression, slope fracturing and intense erosion of tills started. The last glacial–interglacial transition appears to be a major disequilibrium period in the whole Pyrenean region.

Fluvioglacial deposition is dominant in the proglacial zone because of the rapid dumping of 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). These processes most likely happened in the valley during deglaciation, enhanced by the large amount of glacial sediments being exposed, destabilized and eroded as the trunk Garona glacier retreated. High sediment load and discharge flow allowed the formation of large first-generation alluvial fans, during a first very active stage of bedload and debris flow material accumulation.

About 21 ka ago, the Garona glacier retreated upstream of Barbazan (Stange et al., 2014b), 30 km downstream of Les. Thus, deglaciation in Val d'Aran must be younger, probably around 13.7 ± 0.9 ka BP as in the neighbouring 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, took place between ca. 21 and 13.7 ka ago, depending on how fast the glacier retreat was, as soon as the glacier uncovered the valley bottoms.

After this initial phase of rapid alluvial deposition, material availability in the tributary catchments decreased and fluvial activity turned to incise. The distal parts of most fans were cut, their main channels entrenched and the fluvioglacial deposits of the high terraces incised. 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. This second stage supports the notion 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 were formed, fitted into the older ones and reached lower topographic levels as the Garona River incised itself. 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.

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 was an increase in torrential detritism, as well as a slope destabilization, 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 Holocene floods.

Because rivers set the lower boundary for hillslopes, incision along the channel network dictates the local rate of base level fall experienced by each hillslope (Kirby and Whipple, 2012). The Garona River shows different incision rates along the study area, between 1.03 and 1.56 mm yr^{-1} in study area A, and between 0.68 and 1.17 mm yr^{-1} in 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, topography and material availability.

Some studies have calculated fluvial incision rates in other Alpine regions. Fox et al. (2015) focussed on the alpine topography to calculate the incision rate of the rivers in a glacial valley in the Central Alps, but they considered a temporal scale of 400 ka (not only the postglacial incision). The obtained values are between 0.6 and 1.8 mm yr^{-1}. Brocard et al. (2003) used cosmogenic ^{10}Be to date upper alluvial terraces in the Western Alps, in order to estimate incision rates and study the effect of climate and tectonics in river response. The average entrenchment rate over the last 140 ka is 0.8 mm yr^{-1}. These values are within the same order of magnitude as those obtained for the Garona River, even if the timescale and setting differ.

7.3 Implications for river management

According to Mazzorana et al. (2013), characterization 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 and frequency (Macklin et al., 2013), even though they are often not perceptible at human scale. Hence, apart from the anthropogenic actions and present processes, the long-term tendency should be considered for a careful flood hazard management.

The studied stretch of the Garona River corresponds to a mountain river with small anthropic influence characterized by the natural fluvial dynamics, except in a few urbanized areas, where the river is channelized. There are not large dams in Val d'Aran, only some small dams and gauging stations along the study area. They can enhance local incision just downstream of them (Fig. 8a), but it also occurs upstream (Fig. 8b), where it should not be expected. These man-made infrastructures can be of significant importance during flood events, particularly because they can trap vegetation, be clogged and even be seriously damaged. In Val d'Aran, the Arties dam was clogged and broken, carrying an increase of 47 % of the flood peak discharge during the last event, but it only produced some local effects in Arties without any impact in the global flood effects. Often flood risk assessment erroneously involves a perception of stability, believing that changes are exclusively caused by human actions and not by natural processes (Schumm, 1994), downplaying the importance of the river natural dynamics. Keeping in mind the long-term incisive tendency could help managers improve some actions (e.g. maintenance of some structures or design of deeper foundations for specific dykes).

In terms of present processes and flood events in the study area, erosive effects clearly dominate those related to overflow and/or accumulation, inducing episodic short-term entrenchment. We observed that during the 2013 flood, particular features such as bridges and channels influenced the flow, but only locally. Most of the river is not anthropized and was affected by intense erosion. In terms of "induced" effects, channelization dykes partly prevented overflow, intensifying vertical incision (e.g. erosion and dyke scouring in Les, Fig. 7a, b), but also enhanced erosion downstream of these stretches. Some bridges were clogged or they did not have a large enough dimension for the flood discharge, so adjacent areas were flooded and presented some overflow sedimentation, but the flood also caused erosion, affecting bridge foundations. Concerning "natural" effects, in areas slightly or not affected by human influence, incision and bank erosion were the main recorded phenomena, with few overflow points and accumulation areas (Table 2). One of the most significant cases of overflow accumulation occurred due to the erosion and subsequent collapse of a bank in Era Bordeta, which generated a water and sediment wave that covered the opposite bank. Local accumulation zones were restricted to slope decreases (e.g. in Casarilh), small overflows at meanders (e.g. upstream of Bossòst), alluvial fans (e.g. in Vielha) and confluences (e.g. downstream of the confluence of the Valarties River). Accumulation zones were also mostly related to alluvial fans in previous floods (see Table 1) and this is not in contradiction with the generalized incision. Taking into account that the 2013 event was an intermediate one (recurrence interval of 30–50 years) that produced significant erosion, major floods would enhance the morphology evolution, as was described for the major historical floods (Table 1). Channel changes in time can have implications for flood frequency (Gregory et al., 2008), and the entrenchment dynamics can reduce the flooded area and therefore, the expected flooded areas will be less frequently affected. The most important consequence is the destruction of the river banks and the scouring of bridge and dyke foundations. In these areas, protection of engineering works threatened by incision should be a priority (Bravard et al., 1999). Even though we admit that these progressive processes are very difficult to systematize in guidelines, we provide a piece of knowledge that should not be discarded. Present erosion processes seem to be enhanced by the climatic and tectonic history, and the combination of these long-term factors (geologic, tectonic and geomorphological context) with short-term factors (especially local anthropization) is essential to understand the dynamics of the Garona River. This approach considers the complexity of the system as suggested by Kondolf and Piegay (2003), by working with the convergence of evidence instead of using conclusive proofs, and comparing multiple sites, instead of focussing on control sites.

The practical relevance of the long-term dynamics is that it can be integrated in recently developed flood risk management approaches (Rinaldi et al., 2014; Belletti et al., 2015; Gurnell et al., 2015), which consider fluvial geomorphology as a part of a hierarchical framework for hydromorphological analysis. For example, Rinaldi et al. (2014) present the IDRAIM framework as a "comprehensive methodological framework for the analysis, post-monitoring assessment and implementation of mitigation measures" for river-related risks. It highlights the importance of different timescales and space scales for the analysis and monitoring of waterways, ranging from the geologic and geomorphological characteristics of the catchment (10^4–10^6-year geologic scale) to the detailed study of specific river stretches. However, they state that the effective temporal scale preferably used in the field of modern fluvial geomorphology is the medium timescale corresponding to 100–150 years, which is comparable to the scale of human life and is useful for management purposes. The 100-year timescale is very appropriate to detect changes, produced mostly by land use changes (Simon, 1989; Winterbottom, 2000; Liébault and Piègay, 2001; Gurnell et al., 2003; Surian and Rinaldi, 2004; Gallart and Llorens, 2004; Rinaldi and Surian, 2005; Surian, 2006; Rinaldi et al., 2008; Surian et al., 2009), but these are meaningless in Val d'Aran since, at least, 1946. Nevertheless, like Shields et al. (2003), Rinaldi et al. (2014) assert that current trends are more appropriately defined by restricting the temporal scale to the last 10–15 years.

According to Shields et al. (2003), this 10–15-year scale covers most of the hydrodynamic studies for prediction of the system response. Shields et al. (2003) state that the numerical methods dealing with hydraulic geometry relations and planform predictors are best applied to regions with lightly perturbed alluvial channels in dynamic equilibrium for which extensive data sets are available. The weaknesses of these methods are that they can give misleading results when applied outside the domain of the underlying data or when no extensive data sets are available (Allen et al., 1994; Van den Berg, 1995; Shields, 1996; Thorne et al., 1996). Numerical methods that deal with sediment transport and hydraulic variables are usually limited to coarse bed channels, while sediment budgets are best for sand bed streams prone to aggradation. The limitations of these methods are that sediment inflows are usually unknown, most sediment transport relations are imprecise (USACE, 1994) and there is a high level of uncertainty in sediment transport computations (Shields et al., 2003). In the case of bank stability analyses, they fit to channels with cohesive banks higher than 3 m, and their weakness is that these methods require considerable field data (Thorne, 1999). All these kinds of analyses usually reflect a trend of about 10–15 years.

This study considers a broad range of time from the geologic scale to the decadal scale, the latter being represented by the 30–50-year return period floods. These are floods with an effective discharge; that is, they model the channel by erosion, changing its width and depth. The contribution of this study is that the long-term millennial timescale entrenchment tendency is reflected at a 100–150-year human scale (the effective timescale for river evolution prediction according to the IDRAIM approach), which could be imperceptible in 10–15-year timescale detailed studies of channel morphology. In fact, channel incision is a gradual change that has slow, but progressive effects and may carry a significant geomorphic hazard (Schumm, 1994). We think that our approach can help to improve flood risk management under the scope of Jacobson et al. (2003), who state that the surficial geologic records are rarely complete enough to furnish precise predictive models, but they can provide contextual information that can constrain predictions and help guide choices and decisions. This approach to long-term dynamics helps to better assess the present geomorphic changes that are the basis for decision makers. Such an analysis does not necessarily need to be performed systematically, but it is strongly recommended when the geologic and geomorphologic context provides enough morphological evidence, like in the case of the Garona River in Val d'Aran.

8 Conclusions

This paper studies the Garona River on different timescales and space scales by relating the regional geologic and geomorphologic setting to current fluvial processes in order to give insights into the future evolution of the river. Our approach considers complexity and works with the convergence of evidence at multiple sites. In consequence, we conclude that the long-term entrenchment evolution of the area strongly influences the present river dynamics and flood effects, which poses a challenge for flood risk management.

Flash floods and torrential floods represent a hazardous risk in Val d'Aran, where the last moderate event on 18 June 2013 (RP 30–50 years) produced several geomorphological effects, especially bank erosion and vertical incision. The study area is located in the Pyrenean Axial Zone where recent and active tectonics influences drainage network development, evolution and dynamics. The post-orogenic exhumation and uplift (isostatic rebound) seems to have induced river entrenchment since the Miocene. During the last Upper Pleistocene glaciation, the Garona glacier occupied Val d'Aran, so alluvial deposits and landforms found at the valley bottom (two generations of alluvial fans and terraces) were formed during late-glacial and postglacial times. Progressive erosion during the Holocene has shaped the landscape, with an estimated entrenchment rate between 0.68 and 1.56 $\mathrm{mm\,yr^{-1}}$ since deglaciation.

Timescale and process change consideration is essential for river management since present processes are part of the long-term river evolution. The contribution of our work is that the long-term entrenchment tendency concerns the management centennial timescale of the Garona River. In fact, long-term geologic and geomorphologic processes are not imperceptible, but, reflected on the human life scale, are useful for management, related to floods with a recurrence interval lower than 50 years. This kind of study, when enough evidence is identified, can be a complementary step to the hydrodynamic analysis of 10–15-year short-term processes included in river assessment frameworks.

9 Data availability

The underlying data sets of this research are the detailed geomorphological maps of both study areas along the Garona River. The data set of study area A is accessible in Victoriano (2014), which is deposited in the public repository of the University of Barcelona and can be easily accessed (http://hdl.handle.net/2445/57067). The data set of study area B is available in García-Silvestre (2014), but this data set is unpublished.

Author contributions. Marta García-Silvestre, Ane Victoriano and Glòria Furdada designed the investigation and the fieldwork. Ane Victoriano and Marta García-Silvestre carried out most of the fieldwork, data interpretation and discussion, under the direction of Glòria Furdada. The manuscript was drawn up by Ane Victoriano with the help of Glòria Furdada. Jaume Bordonau contributed with the knowledge of the last Pleistocene glaciation, especially in Val d'Aran, and reviewed the manuscript.

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