Hydro-bio-morphological changes and control factors of an upper Alpine valley bottom since the mid-19th century. Case study of the Guil River, Durance catchment, southern French Alps

Changements hydro-bio-morphologiques et facteurs de contrôle d'un fond de vallée alpine depuis la deuxième partie du XIXe siècle. Étude de cas du Haut-Guil, bassin de la Durance, Alpes françaises du Sud

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Abstract *- Much research carried out along rivers at intermediate altitudes has concluded that the general trend of decreasing bedload supply is primarily a result of human action, and only secondarily a response to changes in climate and vegetation. In contrast, we have recently shown that, in the upper reaches of Alpine valleys, the shaping of active channels has been mostly dependent upon hydroclimatic variability, at least during the last fifty years. We propose to apply this hypothesis within a broader temporal framework so as to include the Little Ice Age period. The analysis is based on several types of data: longitudinal and cross profiles, old topographical maps, and aerial photographs. We took account of active channel width and area, sinuosity and incision indices, and engineering structures. We used dendrochronology to improve constraints upon the age of terraces and to help assess the impact of high magnitude floods on riparian forest development. We assert that, whereas the general trend is dominated by channel incision, the overall instability of the active channel is mainly controlled by the passage of low-frequency high-magnitude hydroclimatic events (1957, 2000). Although flood-control structures are generally efficient, the last 50-years of land-use changes have reduced the channel capacity of the Guil, increasing the vulnerability of human installations to damage.*

Keywords: Alpine valley; Channel change; Rare flood; Riparian forest; River management; Little Ice Age

Résumé - De nombreuses recherches conduites sur les cours d'eau de moyenne montagne ont conclu à la réduction du charriage torrentiel principalement pour des raisons anthropiques et secondairement en réponse aux changements climatiques et biogéographiques. Cependant, les auteurs de l'article ont démontré récemment que dans les hauts bassins des vallées alpines, le façonnement des lits de rivière a été la plupart du temps contrôlé par la variabilité hydroclimatique, au moins au cours des cinquante dernières années. Nous proposons d'étendre cette hypothèse à une période plus large incluant le petit âge glaciaire. L'analyse a recours à plusieurs types de données (profils longitudinaux et transversaux, cartes topographiques anciennes et photographies aériennes) pour quantifier la largeur de la bande active, les indices de tressage, de sinuosité et d'incision, et l'impact des ouvrages d'art. La dendrochronologie a été utilisée pour préciser l'âge des terrasses alluviales dans le but d'évaluer l'impact des crues de grande ampleur sur le développement de la forêt riveraine. Alors que la tendance générale (1855-2013) est dominée par l'incision, l'instabilité générale de la bande active du Haut-Guil est principalement contrôlée par l'occurrence d'événements hydroclimatiques de haute magnitude (1957, 2000). Bien que les structures hydrauliques soient généralement efficaces, l'aménagement des rivières des 50 dernières années a réduit la capacité du chenal, accroissant la vulnérabilité et les dommages aux installations humaines.

Mots clés : vallée alpine, métamorphose fluviale, crue exceptionnelle, ripisylve, gestion fluviale, petit âge glaciaire

In the last 200 years, floodplains have experienced more or less significant hydromorphological changes of anthropogenic origin. However, this mode of evolution cannot be extrapolated to all catchments because some floodplains have maintained a relatively 'natural', hydro-climatic controlled functioning, therefore their evolution should be nuanced. There is not a single 'model' of floodplain evolution but a variety of different ones, according to the physical characteristics of the catchment and anthropogenic pressures on the environment. Unlike the Alpine and pre-Alpine valleys at lower altitude, high mountain catchments may have followed a mode of evolution much less constrained by human actions, because of their direct connection with debris sources and the energy of hydro-climatic events. In order to test this hypothesis, we selected one of the major tributaries of the Upper Durance River, the Guil River, which offers the opportunity to assess the respective impact of climate (associated with hydrology) and human activities on the dynamics of the active channel of a torrential river. After specifying the morphosedimentary and human contexts of the catchment and the methodological protocol, 2D spatial variability of the active channel of the Upper Guil River is quantified for the period 1855-2013, before discussing the hydro-climatic and anthropogenic factors of the observed changes.

1 - Hydromorphological changes on the floodplains during the last few centuries: State of the art

During the past few centuries, floodplains and more specifically active channels have evolved according to three possible types (fig. 1):

- Type 1 corresponds to the floodplains under dominant but not strict control of hydro-climatic variability. In Subtype 1a, which includes the Upper Guil River (ARNAUD-FASSETTA and FORT, 2004) and the Argent Double River (ARNAUD-FASSETTA *et al.*, 2002), the dynamics of the valley floor largely depends on the occurrence of low-frequency/high magnitude (LFHM) floods in the catchments, which lead to a 'flash' (*i.e.*, catastrophic) widening of the braided active channels (BELLETTI, 2012). No significant trend in channel narrowing/widening has bee, observed since the 19th century. This model has been validated on many rivers affected by a contrasted torrential regime [*e.g.*, Arizona, USA (BURKAM, 1972); North Queensland,

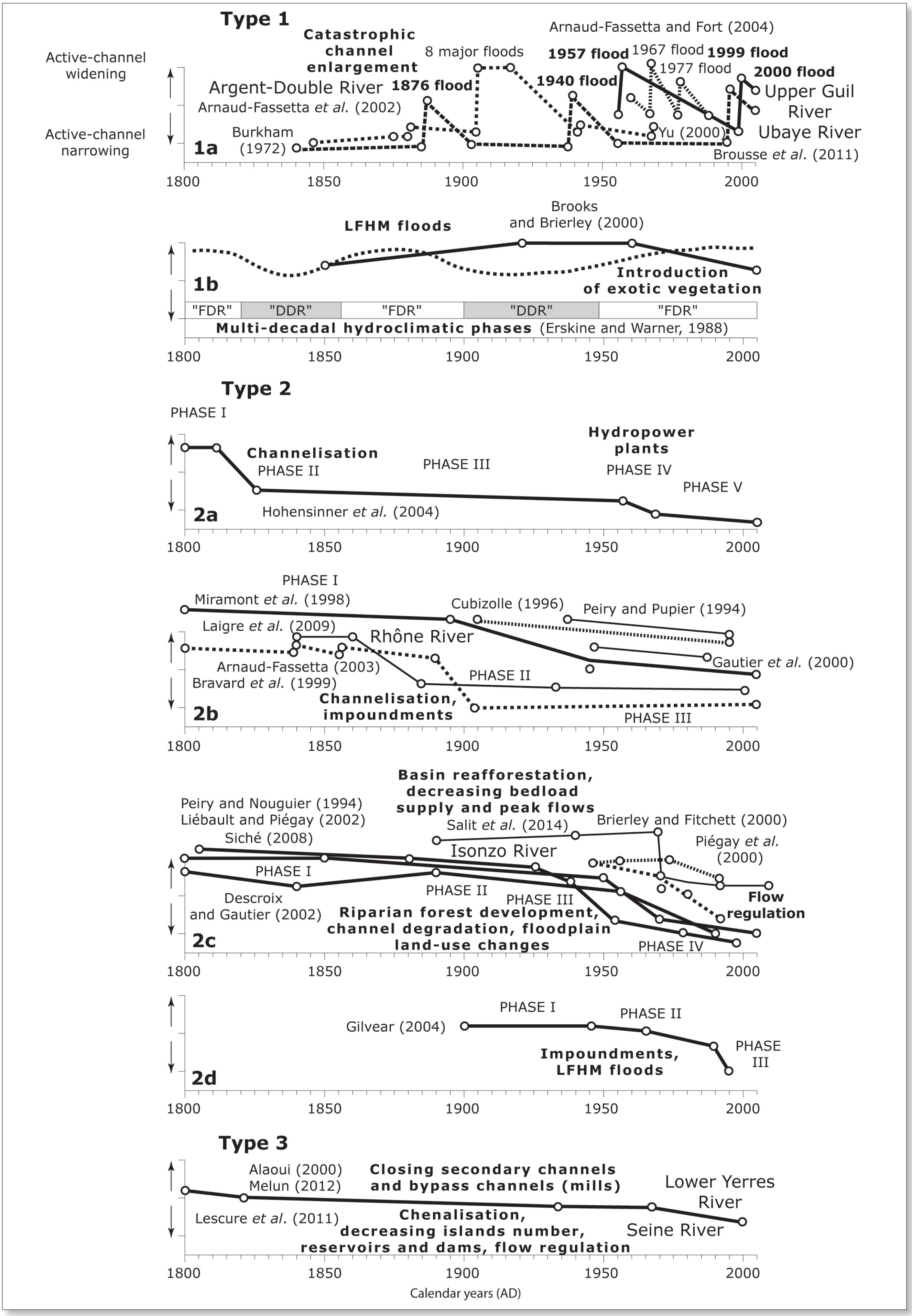

Fig. 1 – Typology of the recent evolution of floodplains. FDR=Flood-dominated regime; DDR=Drought-dominated regime.

Australia (YU, 2000)]. Subtype 1b corresponds to the model initially developed by ERSKINE and WARNER (1988), who have linked the widening of braided active channels of some Australian rivers not to isolated hydro-climatic events but to multi-decadal phases of 'floods-dominated regime' (FDR); in this model, the phases of channel narrowing are linked to phases of low-water ('drought') dominated regime (DDR). More recently ERSKINE and WHITE (1996) showed that the widening of active-channels, continuous between 1935 and 1995, was exacerbated by the largest floods. Finally, the initial model was improved by BROOKS and BRIERLEY (2000), who proposed a new periodisation of the effects in the floodplain during flood and low-water events. Therefore, the period 1850-1920 (FDR) is marked by the widening of active channels whereas the period 1920-1960 (DDR) is characterised by a relative stability of active channels. Since 1960, active-channel narrowing operates in phase with FDR due to the introduction of exotic species such as Babylon Willow, and a decrease in the role of hydro-climatic controls.

- Type 2 includes the floodplains with a hydrodynamic behaviour influenced, to varying degrees and time lags, by human actions (*e.g.*, embankment, channelisation, hydroelectric dams, diversion channels, flow regulation, soil erosion, reafforestation, etc.). Subtype 2a corresponds to the floodplains in which active-channel narrowing is related to early operations of channelisation. The Danube River is part of this subtype: in the Machland region (Austria), the active channel contracted abruptly in the early 19th century (channelisation) and in 1950-1960 (hydropower stations; HOHENSINNER *et al.*, 2004). Subtype 2b is marked by a tendency to active-channel narrowing since the 19th century, with a maximum observed between the late 19th century and early 20th century. The Lower Rhône River illustrates the phenomenon of active-channel narrowing that occurs in response to dyking and channelisation (BRAVARD *et al.,* 1999; ARNAUD-FASSETTA, 2003). Subtype 2c includes rivers marked by a tendency to active-channel narrowing since the second half of the 19th century, with a reinforcement of the phenomenon between 1950 and 1970. This is the model established by PEIRY and PUPIER (1994) on northern French Alps rivers and by LIÉBAULT and PIÉGAY (2002) on pre-Alpine rivers, which also corresponds to the evolution observed in rivers of the southern French Alps (DESCROIX and GAUTIER, 2002). However, the phase of maximum channel narrowing could have taken place earlier, as in the Isonzo River (northern Italy), following the construction, in 1930, of the first large hydroelectric dams (SICHÉ, 2008), or later, for example in response to the flow regulation of the Waiau River (Australia) from the late 1960s (BRIERLEY and FITCHETT, 2000). In Subtype 2d, active-channel narrowing is especially marked in the late 19th century. In the Upper Spey River (Scotland), for example, the active-channel narrowing by dykes was increased by the vertical adjustment (*i.e.*, incision) of the channel during major floods (GILVEAR, 2004).

- Type 3 characterises the floodplains where strong human impact completely hides the effects of hydro-climatic variability. Thus, like most rivers in the Parisian Basin, dominated by a "two-seasons" hydrological regime (*i.e.*, high ordinary waters and floods in autumn, winter and spring, low waters in summer), a silty clay sediment load, and high anthropogenic pressures, the Yerres River (right-bank tributary of the Seine River upstream of Paris) illustrates this type of evolution. The work of ALAOUI (2000) and MELUN (2012) showed that in the early 18th c., the secondary channels (partly natural?) are still numerous in the valley bottom. From 1736 at least, human impacts on the hydrosystem are very strong, resulting in the opening of many diversion channels for the mills. The evolution of the hydrographic network actually depends on the abandonment of mills and diversion channels. In the 20th century, the opening of some artificial channels does not reverse the trend to decrease the number of channels, many of them have been artificial for several decades or even centuries. Floods overflow onto the flood plain, without significant impact on the planform geometry of channels.

This paper analyses a floodplain belonging to Subtype 1a, the Upper Guil River in the southern French Alps. Over the past twenty years, many studies on French Alpine rivers showed that their active channels have undergone significant hydromorphological changes in the second half of the 19th century (JORDA, 1985; BRAVARD and PEIRY, 1993; SALVADOR, 1993; GAUTIER, 1994; PEIRY and NOUGUIER, 1994; MIRAMONT *et al.,* 1998; BALLANDRAS, 2002). In particular, sediment fluxes reduced in connection with the decrease in sedimentary stocks inherited from the Little Ice Age (LIA) and the number of HFLM floods, the attenuation of annual flood peaks by reafforestation of slopes and valley bottoms, the hydraulic works, and agro-pastoral abandonment. Thus, the trend observed since the end of the LIA appears in agreement with the narrowing of active channels and the reduction of the braiding index. More specifically, between 1950 and 1970, the acceleration of the active-channel narrowing in the Prealpine rivers is explained by LIÉBAULT and PIÉGAY (2002) by changes in land use (reafforestation, agricultural abandonment). The Guil, as a river of high altitude and therefore very close to the sediment source areas, despite the anthropogenic pressures, could have had a hydromorphological functioning different from catchments characterised by a lower relief and altitudes.

2 - Study area

The Guil is a torrential river that drains a catchment (730 km^2) situated in the internal zone of the western Alps. With the rivers Ubaye and Guisanne, the Guil River is one of the main tributaries of the Upper Durance River (fig. 2).

The study focuses on the upper section of the Guil River, which extends over 28.8 km between Lake Lestio (2510 m – asl) and Château-Queyras (1350 m; fig. 4). In the studied part of the catchment (317 km^2), the mean rainfall values vary from 828 mm/a (Abriès) to 714 mm/a (Château-Queyras) but they are probably much higher at altitude. Precipitation falls as snow in winter and rain in late spring or early autumn, during the incursion of moist air masses from the Mediterranean (*i.e.*, "*coups de Lombarde*"). The hydrological regime of the Upper Guil River is nivo-pluvial.

2.1 - Geomorphological context

90% of the drainage is concentrated in the range between 1400 m to 2700 m, with a maximum between 2000 m and 2200 m (28%; fig. 3B and 3C). 77% of the catchment is drained by rivers with permanent flow. The hydrographic network is organised as the rectangular type of HOWARD (1967) and the ordination of permanent flows (STRAHLER, 1952) gives the Upper Guil River a rank 5 in Château-Queyras (fig. 3A).

Largely influenced by the geological structure of the catchment and secondarily by the presence of strong torrential cones in the valley bottom, the Upper Guil River adopts a sub-straight path, with a mean sinuosity

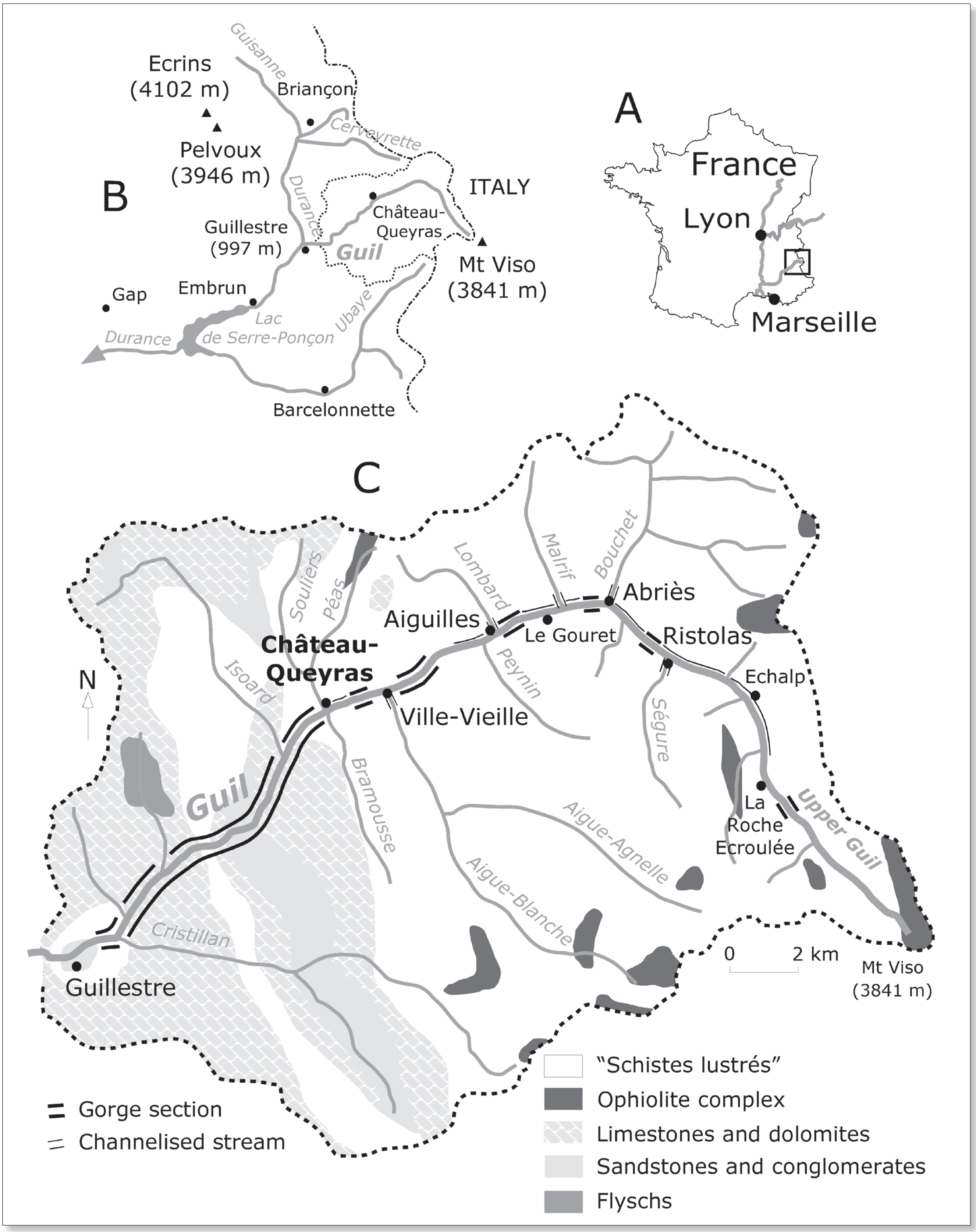

Fig. 2 – The Guil catchment. (A) General location. (B) Location of the Guil River in the Durance hydrographical network. (C) Geological and hydrographical characteristics of the Guil catchment. The study area corresponds to the part located upstream of Château-Queyras.

index (BRICE, 1964) of 1.08 in the year 2000. Upstream from Château-Queyras, 90-95% of the outcrops are the "schistes lustrés" of the intra-Alpine zone, whereas in the remaining parts ophiolites, limestones and dolomites are represented (fig. 2). Strongly tectonised and very sensitive to frost, the schists provide a considerable amount of

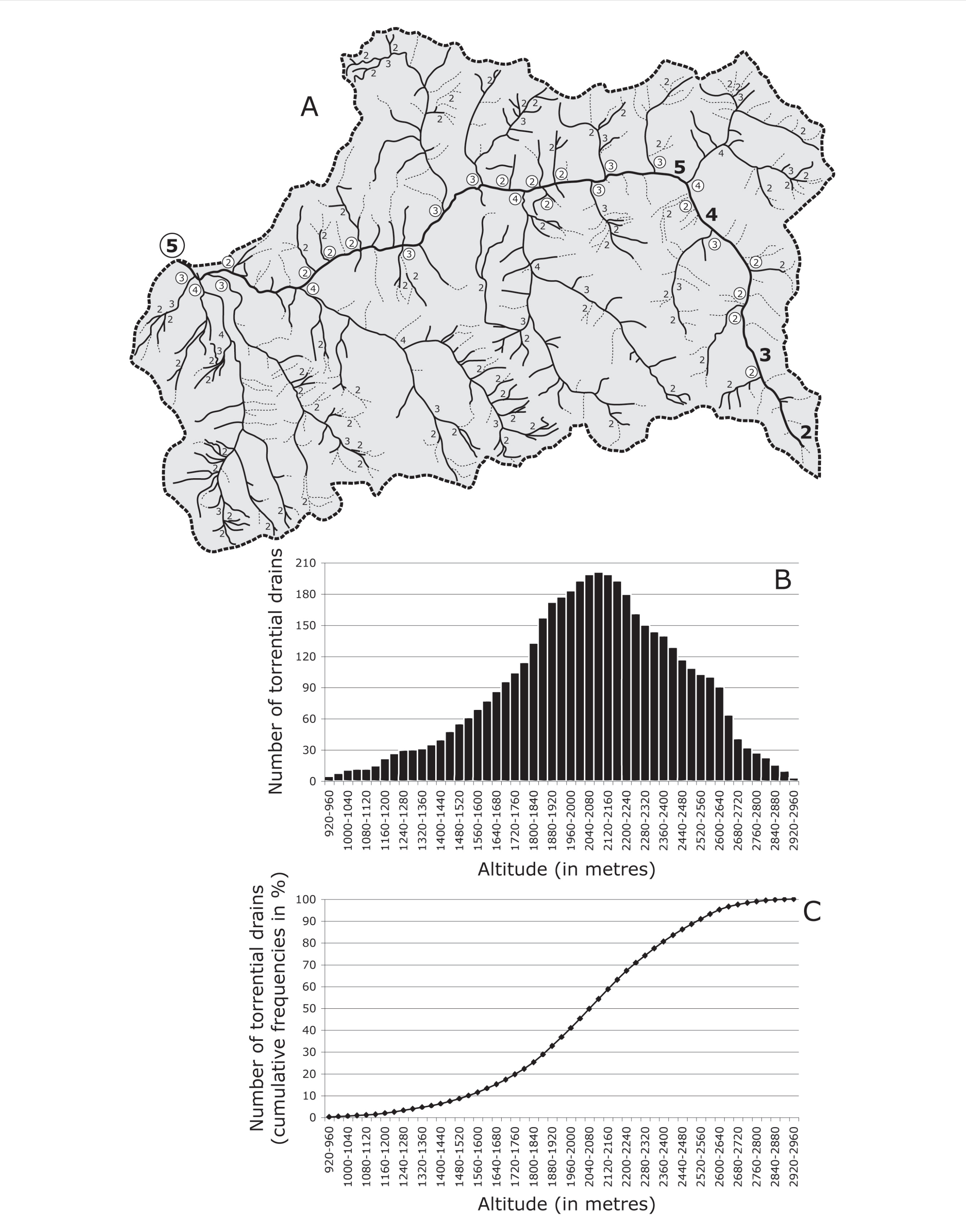

Fig. 3 – The hydrographical network of the Guil River. (A) Channel segments as ordered by the Strahler (1952) system. Upstream of Château-Queyras, the Guil River is a 5th order stream and most of its tributaries are 2nd or 3rd order stream, except for the Bouchet and Aigue-Agnelle streams (4th order). (B) and (C) Link concentration function, plotting the number of torrential drains versus altitude.

debris – mostly flat pebbles (*plaquettes*) and suspension matters (*nite*) – that *via* avalanches, debris flows and landslides, feed the active channels of the Guil tributaries then the trunk channel. The valley is characterised by a strong relief asymmetry, slopes facing west and northwest, moderately inclined and sub-parallel to the westward-dipping schist, opposing very steep anti-dip slopes facing east and southeast. Thus, during the "*coups de Lombarde*", rainstorms coming from the southeast increases the morphological impact on the slopes located mainly on the left bank of the Upper Guil River.

2.2 - Morpho-sedimentary characteristics of the Guil River

The classification of SCHUMM (1977) places the Upper Guil among braided rivers, which implies a strong lateral instability of its active channel. During moderate flows, the riverbed evolves from sectors characterised by divided channels (floodplains) to sectors with a single channel (ancient subglacial and postglacial gorges and/or zones of narrowing of the valley bottom by torrential cones). The longitudinal profile of the Upper Guil River is characterised by an alternation of steep gradients (15-26%), rather frequent in the upstream area, with areas with a moderate gradient (1-6%) where the Guil River really takes the characteristics of a torrential river. The grain size of bed-material load is dominated by pebbles (63 mm<D50<172 mm; fig. 4). There is no longitudinal grain-size gradient although the coarser alluvium is deposited in the upper part of the catchment. Sediment inputs from the tributaries into the active channel of the Upper Guil River are important, but they do not induce a systematic increase of sediment grain size (D_{90} and D_{50}) downstream of the confluences, in constrast with what has been shown on the upper reaches of the catchment (FORT *et al.*, 2002). During flood events, the Upper Guil River is able to completely change the geometry of its active channel due to very high flow competence and sediment transport capacity (ARNAUD-FASSETTA *et al.*, 2005). The specific stream power is high during flood events (50 W/m^2<ω_{30}<1130 W/m^2; mean ~245 W/m^2; fig. 4), which ranks the Upper Guil River among the rivers of high energy according to the typology from NANSON and CROKE (1992).

2.3 - A long history of floods

Historical records mention many catastrophic floods on the Guil River and its tributaries (ARNAUD-FASSETTA *et al.*, 2005). These floods have had a variable impact, either affecting only a few sub-catchments and confluence areas, or the entire catchment and the Queyras villages, as in 1408, 1431, 1791, 1810, 1948, and 1957 (RTM archives; TIVOLLIER and ISNEL, 1938; TRICART, 1958; FANTHOU, 1994). Sedimentary archives associated with other proxies (fossil tree trunks) reflect the torrential activity at least since 4000 years BP (FORT *et al.*, 2002). The presence of very thick alluvial series corresponds to the destabilisation of catchments in relation to environmental crises (JORDA, 1985; BALLANDRAs, 2002).

2.4 - Human activities

Like most other catchments in the southern Alps, the Upper Guil catchment has been affected by the cumulative effects of human activities on the environment: *e.g.* agro-pastoral abandonment, slope reafforestation, torrential control by dams led by the Service of Restoration of Land in Mountain (RTM) and the National Forestry Office (ONF), development of winter and summer tourism. In the Guil's active channel, these actions have affected (i) the development of road infrastructure (embankment of the D947 road, parking, forest roads) and other structures (bridges), (ii) the extension of human activities (area housing, camping, craft area) on the floodplain, (iii) the development of ski slopes and ski lifts, and (iv) the river hydraulics (channelisation, dykes, weirs, irrigation canals, water intake). After the 1957 flood event, money was invested in the restoration of the Upper Guil riverbed rather than its tributaries (Ségure, Garcine, Bouchet, Lombard, Aigue Agnelle), so that most of the hydraulic equipment (check-dams, dykes) in the valley, which reduced the width of the active channels, dates almost exclusively from this time. Currently in the valley there are nearly 1,250 permanent residents, grouped in several villages including Ristolas (90 inhabitants), Abriès (365 inhabitants), Aiguilles (433 inhabitants), and Château-Ville-Vieille (337 inhabitants). These values are often multiplied by 10 or 15 during the tourist season. Finally, development projects in the valley are managed by the Regional Nature Park of Queyras (PNRQ), in charge of elaborating and implementing the River Plan (*Contrat de rivière*) and the Program of prevention against floods (PAPI).

In summary, there are many potential factors controlling the active channel of the Upper Guil River: they are of morphostructural, hydro-sedimentary and human order. Regarding the morphostructural aspect, the gorges and lateral inputs (torrential cones) control the general shape of the valley bottom. The hydro-sedimentary characteristics particularly concern the flood events, which control the widening-aggradation or narrowing-incision of the active channel depending on flow competence and sediment transport capacity of the river, or in other words, the adjustment of two external variables Q_l and Q_s (SCHUMM, 1977; STARKEL, 1983; KNIGHTON, 1998). Adjacent to or in the active channel, the human factor is the presence of the D947 embankment – and its various connections with bridges and parkings – and hydraulic structures.

3 - Methods

Study methods involve the quantification of active-channel planform changes and an analysis of the 2000 flood event in terms of morphogenesis and impact on structures built after the 1957 flood event. These observations have been analysed using hydrographic network characteristics, channel cross-sections, bed-material grain size and hydraulics, channel planform changes, and dendrochronology.

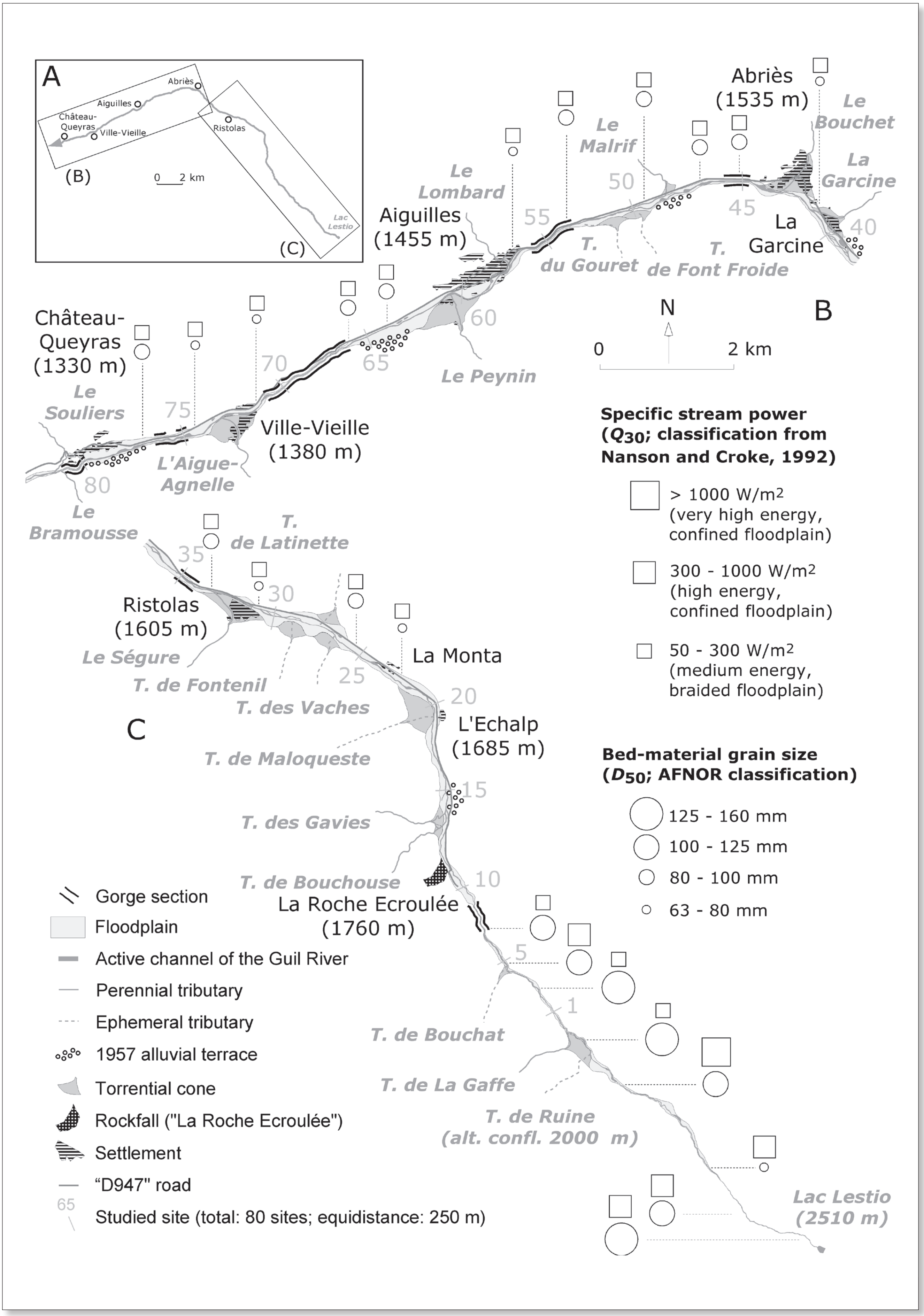

Fig. 4 – Morphosedimentary, hydraulic and anthropogenic characteristics of the Upper-Guil valley bottom. (A) General location. (B) and (C) Downstream and upstream sections, respectively.

3.1 - Hydrographic network characteristics

We used the STRAHLER (1952) approach for classifying segments of channel in terms of stream order. Bifurcation ratio (R_b) is expressed as:

$Nu\text{-}1/Nu$ (1)

where Nu is the number of streams of order u. Drainage density (Dd) was defined by HORTON (1945) by:

åL/Ad (2)

where åL is the total length in a basin of area Ad. As proposed by GUPTA and MESA (1988), we devised a link concentration function for the Guil catchment, which represents the number of channel segments at various elevations above the catchment outlet.

3.2 - Bed-material grain size and channel hydraulics

In order to characterise the grain size of the bed-material, sediments were collected at each cross-section. For the gravel material, CHURCH *et al.* (1987) recommended that the weight of the coarsest particle does not exceed 1% of the total sample weight. In the Guil River and its tributaries, the coarsest particle weight never exceeded 5% of the total sample. Samples were analysed both in the field and the lab using standard techniques as suggested by WOLMAN (1954), FOLK (1980) and THORNE (1998). For grain-size characterisation, the entire sample was taken. In this sample, the >5 mm fraction was weighed (using a pocket rod) and measured in the field in order to quantify the longest axis of each particle. The <5 mm fraction was analysed in the lab to be weighed and sieved (using dry-sieving techniques, AFNOR standard). Connecting the two grain-size curves (>5 mm and <5 mm fractions) was done using a protocol developed in the laboratory of the Paris-Diderot University. For each sample, grain-size data were characterised by calculating $D50$. As indicated by DOYLE and SHIELDS Jr. (2000), D_{50} best represents the grain-size distribution.

For hydraulic calculations, NANSON and CROKE (1992) identified three major types of floodplain (high-energy, medium-energy, low-energy), defined according to specific stream power. This latter was calculated for 21 sites in order to quantify the hydrodynamic characteristics of the Guil River. The calculations were based on measurements of slope and channel geometry carried out after the June 2000 flood event (Q_{30}). The specific stream power ($\boldsymbol{w}$) has been calculated using the BAGNOLD (1980) equation:

$\boldsymbol{w}$ (in W/m^2)$=(\rho wgQS)/W$ (3)

where ρw is water density (in kg/m^3), g is gravitational acceleration (in m/s2), Q is discharge (in m^3/s), S is slope (in m/m), and W is active channel width (in m). In the absence of available data at each study site, Q in Eq. 1 has been estimated from the equation in ROTNICKI (1991):

$Q=(0.921/n)AR^{0.67}S^{0.5}+2.362$ (4)

where n is Manning's resistance coefficient, A is cross-sectional area (in m^2), and R is hydraulic radius (in m). The JARRETT (1985) equation was used to determine an initial value of n in Eq. (3):

$n=0.32S^{0.38}R\text{-}^{0.16}$ (5)

The Jarrett equation is the best one to estimate roughness on higher-gradient streams (cobble- and boulder-bed material) with slopes varying between 0.002 and 0.039, and hydraulic radius varying between 0.15 m and 1.68 m, that corresponds to the characteristics of the studied channel sections in the upper Guil River.

3.3 - Channel planform changes

The identification of channel planform changes primarily involves the use of sequential sets of old maps (fig. 5), *i.e.* for 1855 (1:25,000), 1889-1895 (1:25,000), 1928-1933 (1:25,000) and 1975 (1:25,000), and aerial photographs, *i.e.* for 1956 (1:25,000), 1957 (1:15,000), 1999 (1:25,000), 2000 (1:8000) and 2013 (Google Maps). Each selected document was scanned with a resolution of 1200 dpi. The visual quality of photographs – mostly the contrast – has been enhanced with Photoshop. Four landmarks were chosen to rectify the geometry of each photograph, with reference to IGN topographic maps (1:25,000) of Guillestre and Mont Viso.

80 sites, selected every 250-300 m, allowed the study of a torrential section of 23.3 km. The coverage of the Upper Guil River by old maps and aerial photographs is 81%, the very first kilometres (upstream) could not be considered because they were not photographed in 1956, 1957 or 2000. At each site, measurements have been done on transects oriented perpendicular to the active channel (ARNAUD-FASSETTA and FORT, 2004).

Four geomorphological variables were quantified by photo-interpretation: (i) the surface of the active channel, (ii) the width of the active channel, (iii) the braiding index and (iv) the sinuosity index. The 'active channel' (OSTERKAMP and HEDMAN, 1982) corresponds to the extent of water channels and non-vegetated pebble bars (RUNDLE, 1985). Its width was measured directly on the computer screen; the precise location of the points of departure and arrival of each transect was facilitated by an enlargement of the pictures by about 800-1600% relative to the original scale. Width measurements were supplemented by calculations of area obtained by quantifying the amount of forested islands from the envelope curve of the active channel. Metric calculations were made using Canvas software. We checked the validity of width measurements acquired from orthorectified aerial photographs, and compared them with *in situ* measurements (n=15) with a theodolite (fig. 6). The error margin obtained is fairly acceptable, with variations in the range of ±8% (mean: 4%).

Regarding the braiding index (B_I), we have chosen to use HOWARD *et al.* (1970)'s index, which is one of the best-suited for the purposes of our research (THORNE, 1997). It corresponds to the average number of anabranches by section -1. The sinuosity index (S_I) was defined by J.C. BRICE (1964) as the 'channel length/straight-line valley length' ratio. In the case of the Guil River, SI is the mean value of three river segments ([from the source to Echalp]; [from Echalp to Abriès]; [from Abriès to Château-Queyras]), to minimise calculation exaggerations resulting from the rectangular shape of the valley. When the active channel was formed by multiple channels, SI was calculated along the main channel.

Old photographs (late 19th and early 20th century) taken by inhabitants in the major villages of the Guil valley

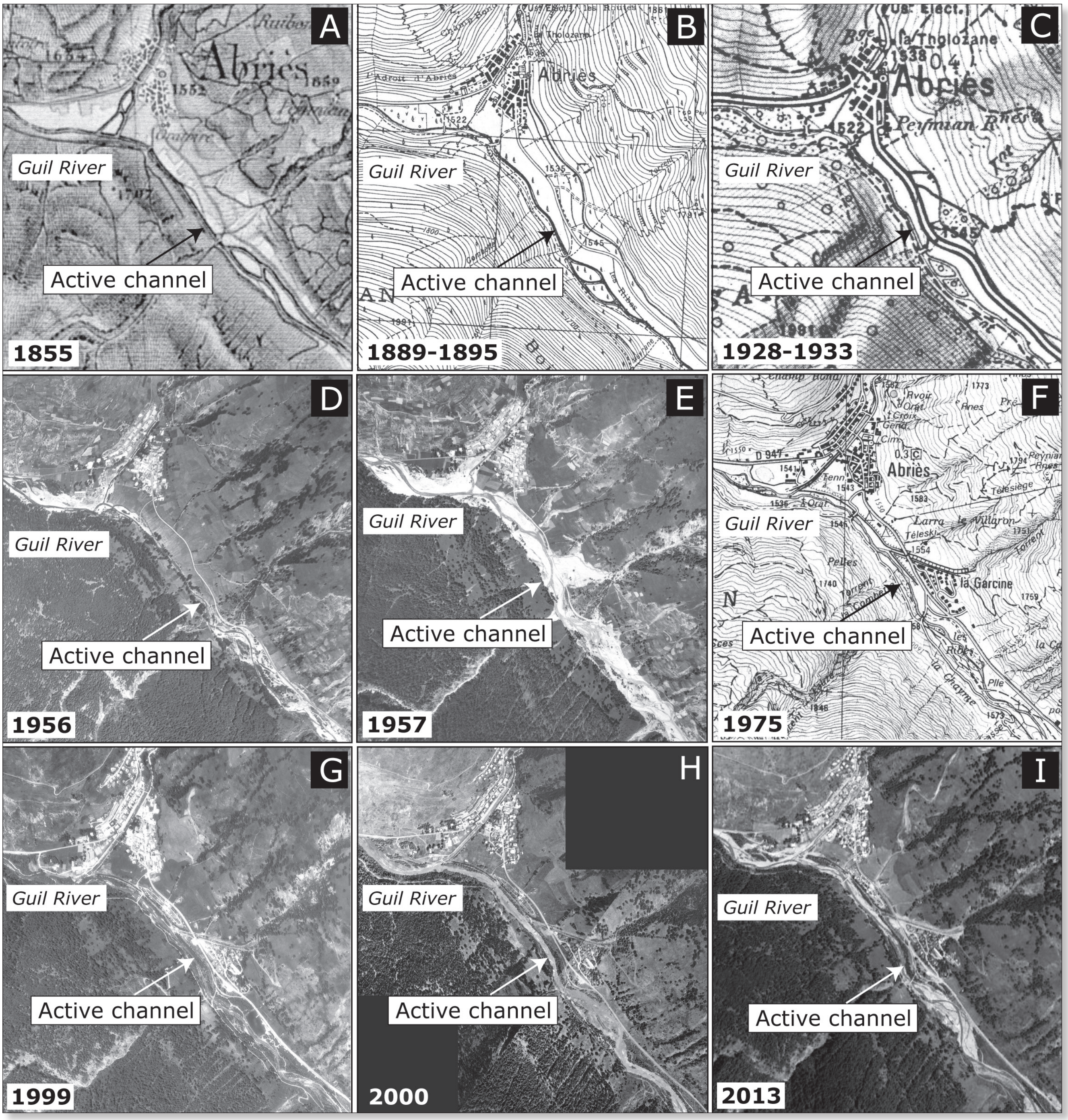

Fig. 5 – Recent evolution (AD 1855-2013) of the Upper-Guil active channel in the sector of La Garcine-Abriès. (A), (B), (C) and (D) Note the relative stability of the active channel. (E) The flood of June 1957 has contributed to the significant widening of the active channel. Note the importance of lateral sediment supply on both slopes and the almost systematic destruction of riparian forest. (F) and (G) The D947 road now encroaches on the floodplain. In the absence of LFHM flood, the riparian forest is restored and the Upper Guil River adopts a simple, common channel pattern (*i.e.*, single channel or two braided channels). (H) The flood of June 2000 once again contributes to the active-channel widening. Note the widespread destruction of riparian forest and the active-channel widening upstream of La Garcine stream. (I) The Guil active channel is narrower than in 2000, but the floods of the late 2000s tend to maintain a large, aggraded active channel. Note the new ski tracks across the forested slopes.

(FERRAND *et al.*, 2003) were compared with photographs of the same sites taken in July 2005 (fig. 7). The data acquired by photo interpretation were supplemented by field observations made between 1999 and 2013.

3.4 - Dendrochronology

Dendrochronological studies are based on the recent, unpublished work of BARCAT (2005) on the recolonisation of the 1957 alluvial terraces of the Upper Guil River (fig. 8). 103 samples from larch trees (*Larix decidua* Mill.) were taken with an increment borer ("*tarière de Pressler*"). Assuming tree development postdates flood aggradation, the tree-ring counts allowed us to place an age constraint on flood aggradation and discuss the assessment of the impacts of large-magnitude floods on the banks and riparian forest development.

3.5 - Anthropogenic impacts

We sought to determine the role played by human activities and structures in the active-channel dynamics of the Upper Guil River. Several semi-quantitative variables were taken into account: crop expansion,

Fig. 6 – The active channel of the upper Guil River. (A) Section upstream of Ristolas immediately after the flood of June 2000. (B) Correlation between values of active-channel width obtained by field measurements and those deduced from aerial photographs (2000 flood).

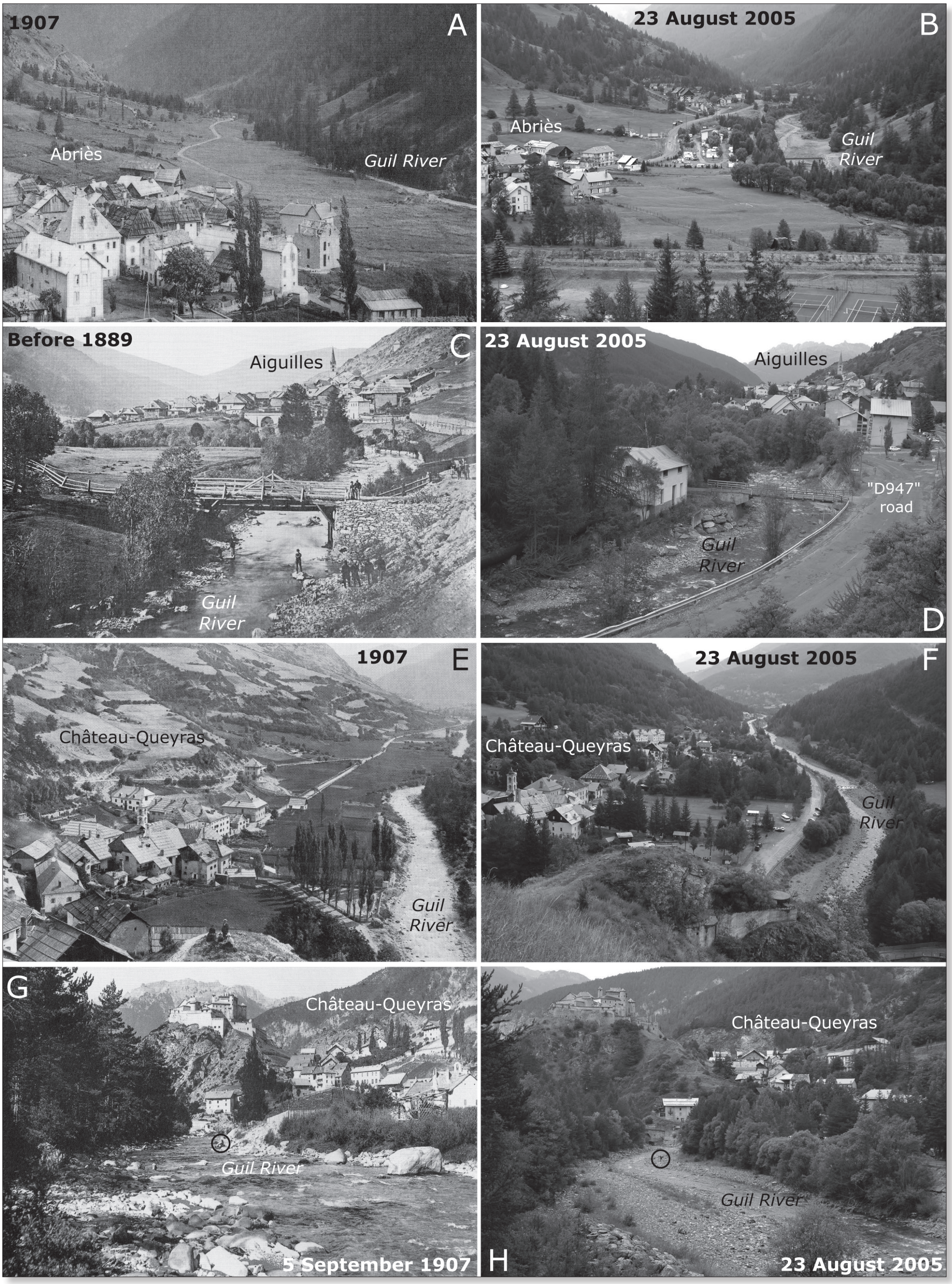

Fig. 7 – Evolution of the Upper-Guil valley between the late 19th – early 20th centuries and 2005, reconstructed using two sets of photographs. (A) Note the narrow channel at the foot of the left-bank slope, the sparsity of the riparian forest, the valley floor and the slopes (especially on the right bank) occupied by fields, and housing developed on the Bouchet alluvial cone. *Photo: Ferrand* et al.*, 2003*. (B) The channel, which has been widened, is now surrounded by a dense riparian forest, while the habitat occupies part of the valley floor, particularly on the right bank. Note also the development of tourist activities (tennis courts on the Bouchet alluvial cone) and reforestation of slopes linked to agricultural abandonment and reforestation campaigns undertaken by the RTM and ONF. *Photo: G. Arnaud-Fassetta, 2005*. (C) Note the relatively narrow active channel, the presence of riparian vegetation; both slopes and valley bottom are sparsely wooded and dominated by crops and hay meadows. *Photo: Ferrand* et al.*, 2003*. (D) Note the forest recolonisation on the slopes and on the valley bottom. The active-channel width is roughly the same as in the late 19th century, despite the implementation of the D947 road embankment. *Photo: G. Arnaud-Fassetta, 2005*. (E) Note the many hay meadows on the slopes and the presence of a narrow active channel near the village. *Photo: Ferrand* et al.*, 2003*. (F) The Guil River has the same width, but moved to its left bank (effect of the 1957 flood). The slopes are more densely wooded while habitats, tourism and roads have developed on the valley floor. *Photo: G. Arnaud-Fassetta, 2005*. (G) The active channel consists of gravelly debris, with many large blocks, several metres in size. (H) The alluvial filling seems less thick and the grain size of the alluvium appears to have decreased, while the ripisilve is denser, especially on the right bank.

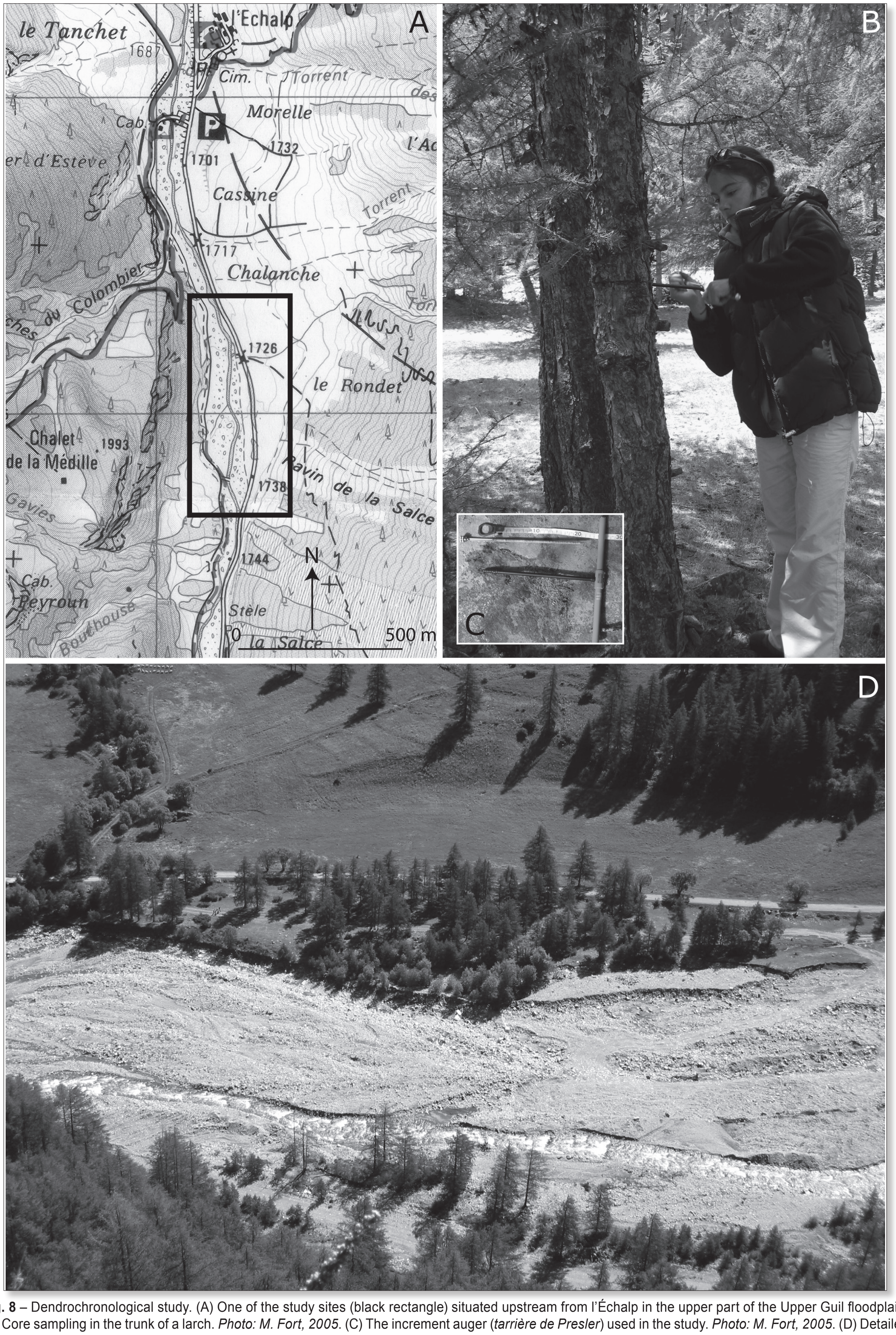

Fig. 8 – Dendrochronological study. (A) One of the study sites (black rectangle) situated upstream from l'Échalp in the upper part of the Upper Guil floodplain. (B) Core sampling in the trunk of a larch. *Photo: M. Fort, 2005.* (C) The increment auger (*tarrière de Presler*) used in the study. *Photo: M. Fort, 2005.* (D) Detailed view of part of the floodplain selected for the dendrochronological study. The sampling was done on the 1957 alluvial terrace located on the right bank of the active channel.

reafforestation, dams on tributaries, channel rectification, buildings on the floodplain, ski tracks. During the past half century, the embankment of the D947 road joining Château-Ville-Vieille and La Roche Écroulée, built on the right bank of the Guil River, has played a key role in narrowing the active channel (ARNAUD-FASSETTA and FORT, 2004). This structure has been taken into account, including (i) its presence (or not) along the active channel, (ii) its destruction (or not) following a flood event, and (iii) the width of the active channel that has been disconnected, following the construction of the road embankment. Thus, we were able to assess and quantify its role in the process of active-channel narrowing (1957-1999) and widening (1956-1957, 1999-2000).

4 - Results: Active-channel planform changes between 1855 and 2013

4.1 - General trend

The drainage density of the Guil catchment is 1.09 km/km^2 (mean) and increases (1.24 km/km^2) upstream from Château-Queyras. The average bifurcation ratio is higher than the mean value (1.89) between the rivers of order 2 and 3 (2.01), and between the rivers of order 3 and 4 (2.24).

From a general point of view, there is no statistical trend with regards to changes in the active-channel planform of the upper Guil River between 1855 and 2000 (fig. 9A). There is a high longitudinal variability of the surface [coefficient of variation (V=s/x=0.560)] and width (V=0.583) of the active channel, and braiding index (V=1.104). The coefficient of variation of the sinuosity is low (V=0.022). The active channel widens at the same time as the braiding index strengthens in floodplain areas, while the active channel contracts in the gorges or confluence areas, where the braiding index is significantly reduced, locally down to zero. Local factors (*i.e.*, bridges) may cause the reduction or increase of channel width, as is the case downstream of the Peynin cone (fig. 4). There, the flood wave of the Guil River is deflected by the Peynin torrential stream against the D947 road embankment, then back towards the cone toe downstream of Peynin Bridge. Finally, 2D spatial variability of the active channel largely depends on the evolution of the hydrological/sedimentary regime of the Upper Guil River. Periodisation that follows will help to analyse the role of flood events and the resilience (*i.e.*, relaxation time) of the river between two major hydrological events.

4.2 - From 1855 to 1956

Between 1855 and 1956, the Upper Guil catchment was affected by eleven flood events. Ten of them [1858; July 1897 (Guil River); 19-25 September 1920 (Guil River); 22 June 1941 (Brasc River); 29 August 1946 (Brasc River); 12 August 1947 (Brasc River); 24 July 1952 (Brasc River); 8 June 1953 (Peynin River and Guil River); 29 September 1953 (Guil River); 21 August 1954 (Brasc River)] were of moderate magnitude according to their variable extent. The 12-15 May 1948 flood (Bouchet River and Guil River) was certainly the most intense event of the period, affecting several villages and hamlets of the catchment, including Le Roux, Abriès, Aiguilles, and Château-Ville-Vieille. In total, several low-magnitude flood events affected the Guil catchment between 1855 and 1956; their frequency increased between 1941 and 1954. No large floods affected the catchment, as was the case for the following period. The surface of the active channel ranged from 0.57 km^2 (1855) to 0.58 km^2 (1956), increasing by only 2% (fig. 9A). The predominant active-channel width ranged between 10 m to 20 m until 1956 when it increased to 20-30 m, due to the occurrence of moderate floods a few years before 1957, including the 1948 flood event (fig. 10).

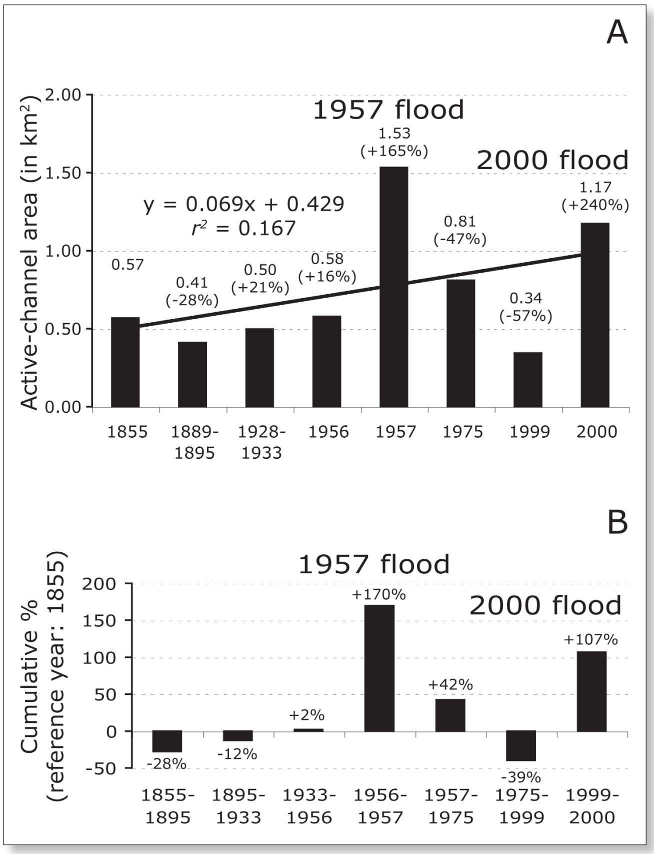

Fig. 9 – Evolution of the active-channel area of the Upper Guil River between 1855 and 2000. (A) Note the absence of significant trends and the impact of the 1957 and 2000 floods (increase of active-channel area by 165% and 240%, respectively). (B) Note the narrowing-widening cycle and the leading role of large floods. In 2000, the active channel increased by 107% compared to 1855.

4.3 - From 1957 to 2013

On June 13th-14th, 1957, the Guil valley recorded a flood considered as a reference hydrological event. Its maximum discharge exceeded Q_{100}, reaching 220 m^3/s in Abriès and 315 m^3/s in Aiguilles (KOULINSKI and LEFORT, 2000). The flood almost affected the entire valley bottom, causing, by its extreme flow competence (*i.e.*, blocks of 35 t carried into the gorges of Château-Queyras), an important mobilisation of: the solid bed-material load, the products of bank erosion, together with the reworking of snow avalanches, landslides and debris flows on the mountain slopes (TRICART, 1958, 1961b). The abundance of sediment supply by the upper drainage system led to an important aggradation on torrential cones. In total, the whole hydrosystem was

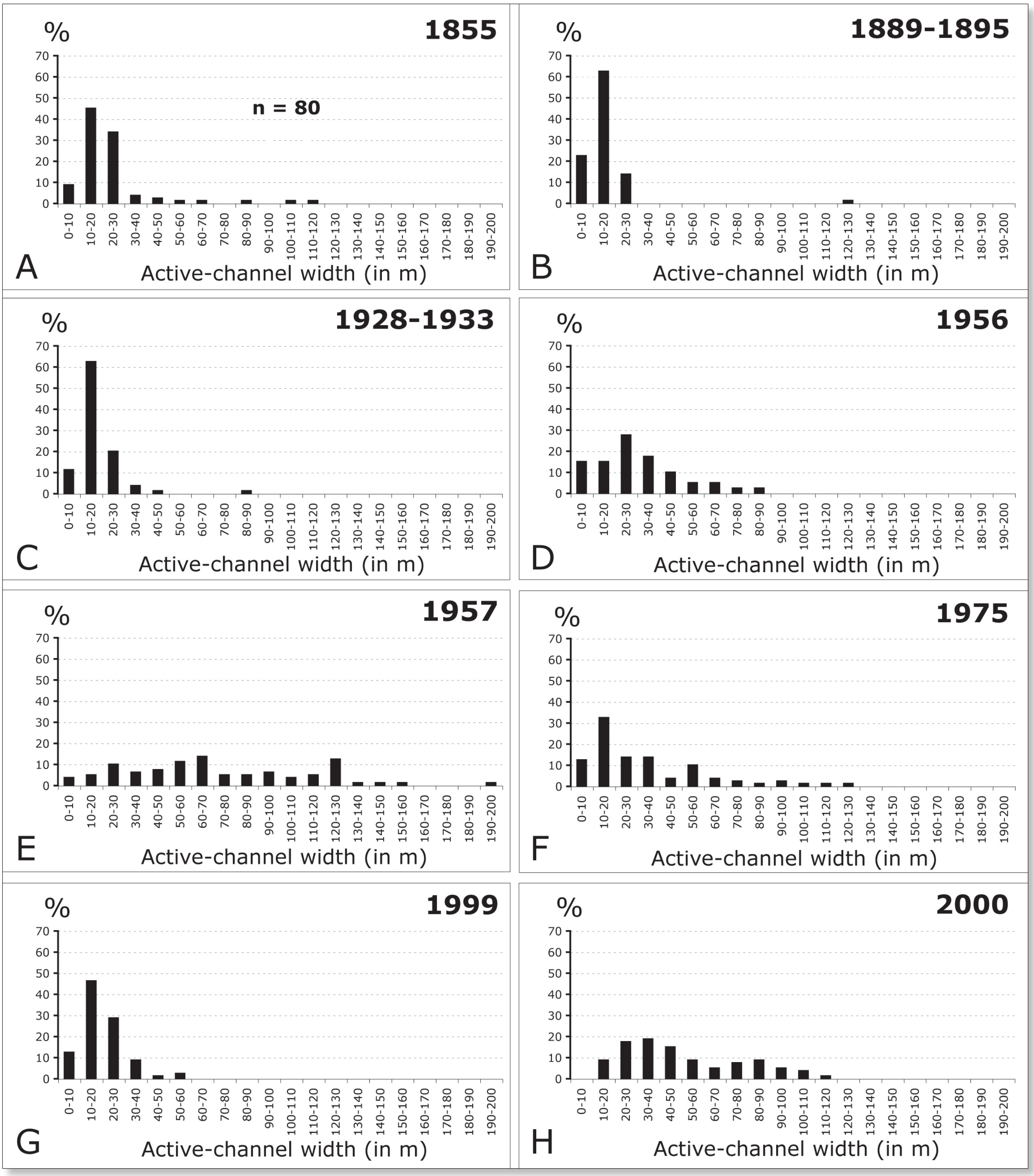

Fig. 10 – Frequency distributions of active-channel width in the upper Guil River at various dates (1855, 1889-1895, 1928-1933, 1956, 1957, 1975, 1999, 2000), derived from 80 values for each one. Note the three types of distribution, with Type 1: sorting and mode well marked corresponding to situations of rare flood events (*e.g.*, 1855, 1889-1895, 1928-1933, 1999); Type 2: histogram (poor sorting) and multimodal distribution corresponding to flood events (*e.g.*, 1957, 2000); and Type 3: relaxation time spanning a few years after the passage of one to several floods of moderate magnitude (*e.g.*, 1956, 1975).

undergoing significant hydromorphological changes and serious damage estimated to be around 100 million francs (TRICART, 1961a), or ~15 million euros. During the months following the 1957 flood event, a major operation of riverbed restoration was undertaken (channelisation, D947 road embankment) along the Guil River and its tributaries where the damage was significant.

The analysis derived from aerial photographs shows that the flood of June 1957 strongly increased the surface area (1.53 km^2) of the Upper-Guil active channel by 165% compared to 1956. Active-channel widening is widespread throughout the study area, but varies depending on the sector. Significant changes are recorded not only in the floodplain areas (Les Faisans, La Chayme, Aiguilles, Les Planissaux, Château-Queyras) but also along the axis of the torrential cones (Garcine, Lombard, and Aigue-Agnelle streams), which frontal lobes prograde in the trunk channel during the flood peak, before being eroded at

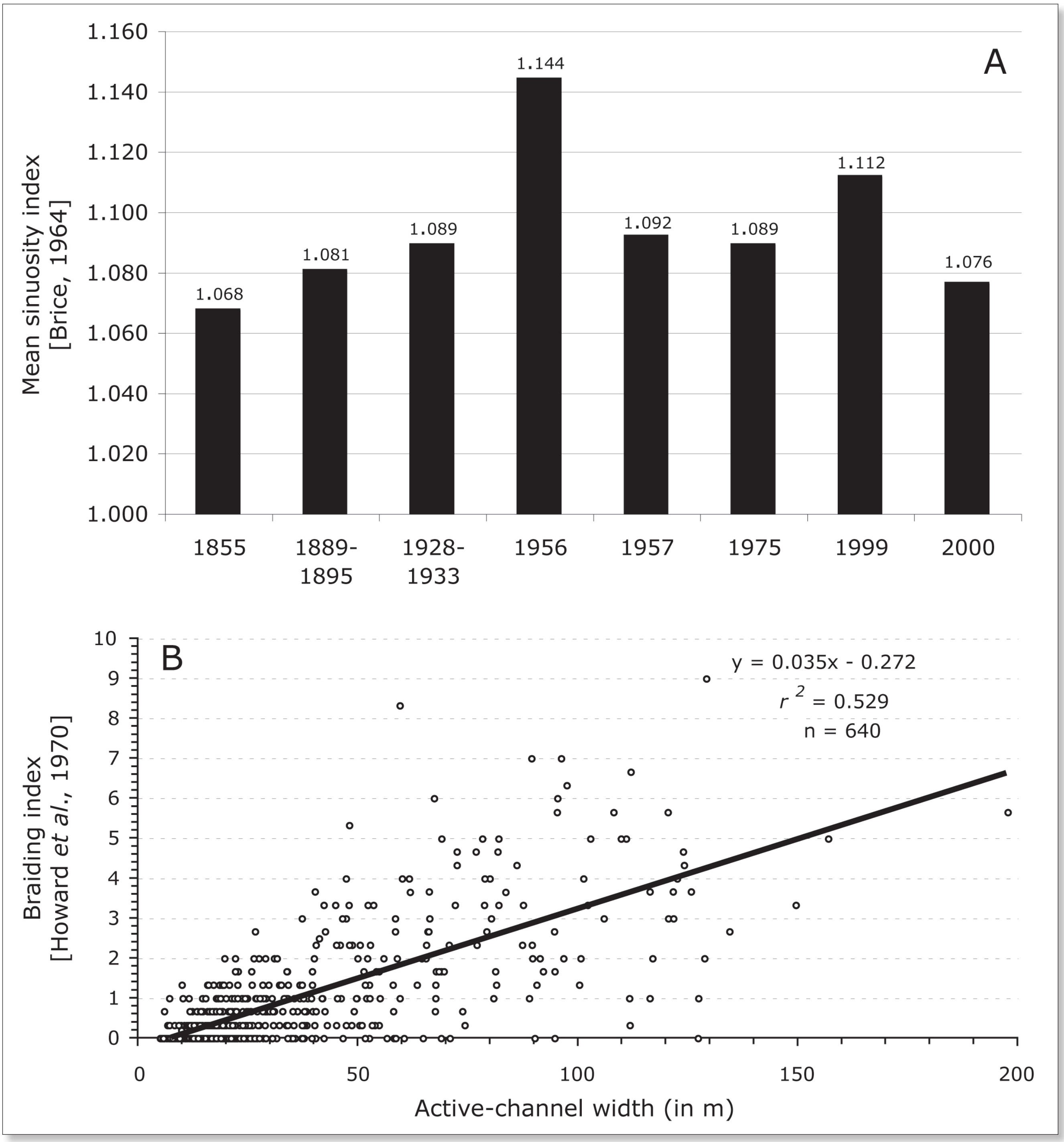

Fig. 11 – (A) Correlation between the active-channel width and the braiding index of the Upper Guil River between 1855 and 2000 (640 values). There is a fairly good correlation between the two variables, with a significant coefficient of determination (r^2) based on an error margin (α) of 0.02. (B) Evolution of the sinuosity index of the Upper Guil River between 1855 and 2000. Between 1855 and 1956 and, to a lesser extent, between 1957 and 1999, the sinuosity increases due to the absence of major floods. The channel is slightly less sinuous in 2000 than 1957.

the end of the flood event. The maximum variations in the active-channel width occurred in the sectors of torrential cones, in the Aigue-Agnelle River in particular. The extreme values of active-channel widening increased gradually downstream, according to the increase of the sediment transport capacity of the river.

The 1957-1999 period is representative of the evolution of the Upper Guil active channel between two LFHM floods. Two flood events of moderate magnitude affected the catchment, those of spring 1973 (Aigue-Agnelle River) and the 26th June 1994 (Aigue-Agnelle River). In June 1999, the surface area of the active channel (0.34 km^2) represents only 23% of the area measured in June-July 1957 (fig. 9A). This phenomenon is accompanied by a systematic narrowing of the active channel, whose average width increased from 10 m to 20 m (fig. 10). Except at a few sites, the channel narrowing is so marked that it allows the 1999 active channel to remain within the limits of that in 1956. Thus, its surface in 1999 is only slightly more than half (58.6%) of that of the surface in 1956. The exacerbation of channel narrowing is explained by (i) the structures (*i.e.*, the D947 road embankment) set up after the 1957 flood and (ii) the relative absence of morphogeneous, hydroclimatic events during the considered period.

From June 10th to 14th, 2000, the Upper Guil catchment is once again affected by a new LFHM flood event. Heavy rains, associated as in 1957, to a Lombarde event, are at the origin of the flood. Unlike June 1957, when the rains were widespread throughout the catchment, the rain cells of June 2000 primarily affected the upstream part of the Upper Guil basin, around Mt Viso, while most of the slopes were already gullied. In total, the hydromorphological impact of this Q_{30} flood event (maximum discharge in Abriès: 120 $m^{3/s}$) was important: flooding and deposition of gravels in the floodplains, repeated bank cuts, significant hydrographical changes, serious material damage estimated only for bridges, dykes, embankments and the D947 road to ~4.6 million euros (FORT *et al.*, 2002; ARNAUD-FASSETTA *et al.*, 2005). The morphodynamic effects of the flood of June 2000 were all the more remarkable because the flood occurred after a period of 'hydrological calm' quite different from 1957, where the destabilisation of the hydrosystem was prepared by a series of floods between 1941 and 1954 (see the discontinuous and sparse riparian forest on aerial photographs from 1956).

The flood of June 2000 led to a significant increase (240%) in the active-channel area (1.17 km2) compared to 1999 (fig. 9), accompanied by an increase in the active-channel width, which averaged 30-40 m, varying between 10 m and 120 m (Chayme plain; fig. 10).

In total, the active channel of the Upper Guil River more than doubled (107%) between 1855 and 2013 (fig. 9B). For the same period, there was also a positive correlation between the active-channel width and braiding index, while the sinuosity index tends to decrease during LFHM flood events (fig. 11).

5 - Discussion: What part of active-channel changes is devoted to hydroclimatic variability and/or human factors?

5.1 - General considerations

In general, the morphogenesis of upper Alpine environments is closely related to the frequency and magnitude of hydro-climatic hazards. Indeed, violent summer or autumn rain storms are capable of rapid reinforcement of competence and sediment transport capacity of flows, leading (i) on the slopes, to the extension of gullies and multiplication of debris flows – especially in the absence of protective forest cover – and (ii) in the valley bottoms, to the adjustment of geometry (*i.e.*, widening, aggradation/degradation) of river beds and to large aggradation on alluvial cones. Stratigraphic sections recently dated in the Peynin catchment (left bank tributary of the Upper Guil River) show the recurrence of such phenomena for at least 4,000 years (FORT *et al.*, 2002). In the Upper Guil catchment, the impact of hydro-climatic hazards have been exacerbated by (i) topo-structural constraints (*i.e.*, steep slopes facing east and south-east), (ii) lithological characteristics (*i.e.*, the presence of "*schistes lustrés*") and (iii) more locally by the action of the agro-pastoral communities. Nevertheless, the fact that this high mountain catchment has (i) long remained on the fringes of large settlements and (ii) always been affected by erosion and large sediment yields (avalanche corridors/cones and scree cones downstream of rock (schists) ledges; gullies on slopes >50%; channel incision and bank erosion in river beds) *a priori* gives greater weight to hydro-climatic factors in shaping the long-term morphodynamic evolution of the valley.

5.2 - Human activities: a secondary factor

For 150 years, the Guil catchment has been affected by diverse human activities, which are illustrated in fig. 12. Human impacts have had variable hydro-morphological effects on the environment. The expansion of crops, pastures and especially the ski tracks on slopes increased runoff, hence flood peaks and the occurrence of debris flows and landslides. Conversely, reafforestation of slopes reduced flood peaks and the extension of debris flows and landslides. The building of check dams in the valley bottom of the Guil tributaries decreased the general hydraulic gradient, the specific stream power, the sediment transport capacity, and the flow competence of torrents. These results are counteracted by the adverse effects related to channel rectification, that increases the channel capacity and reduces the flow competence, specific stream power, and transport capacity. The extension of built areas on the flood plain led to soil compaction, thus reducing the infiltration capacity, the narrowing of active-channels, and the decrease of flood-dissipation areas. In the Guil valley, zones of flood expansion were mostly reduced by the building of the D947 road embankment, which reinforced flood peaks, flow competence, specific stream power, sediment transport capacity, channel incision, whilst contributing to a significant narrowing of the active-channel.

In fact, human activities have often produced opposite effects. But the only really decisive effect of human actions in the valley was the D947 road embankment. This ubiquitous structure was built on the right bank of the Upper Guil River in the gorges, at the base of concave slopes, and even on the flood plain (fig. 6 and 13). It is certainly the most binding structure in the valley bottom and its presence has implications both in terms of widening and narrowing of the Upper Guil's active channel. The impact of the D947 road embankment on the valley-floor functioning was quantified. Built with unconsolidated materials, the embankment acts as a "fuse" when it is eroded and in these conditions, the active-channel can rapidly widen during LFHM flood events. In 1957, the destruction of the embankment was almost general, but more specific in the upstream part of the Upper Guil in 2000, according to the higher magnitude of the last event in the upper part of the catchment. When the embankment was not destroyed, channel widening occurred on the opposite bank by reflection of the flood wave on the structure. In addition, the embankment acts by disconnecting the slopes and the floodplain. Lateral supplies are no longer in specific sectors (alluvial cones, non-embanked sections).

Finally, the D947 road embankment participated in the active-channel narrowing between 1957 and 1999 (fig. 13C).

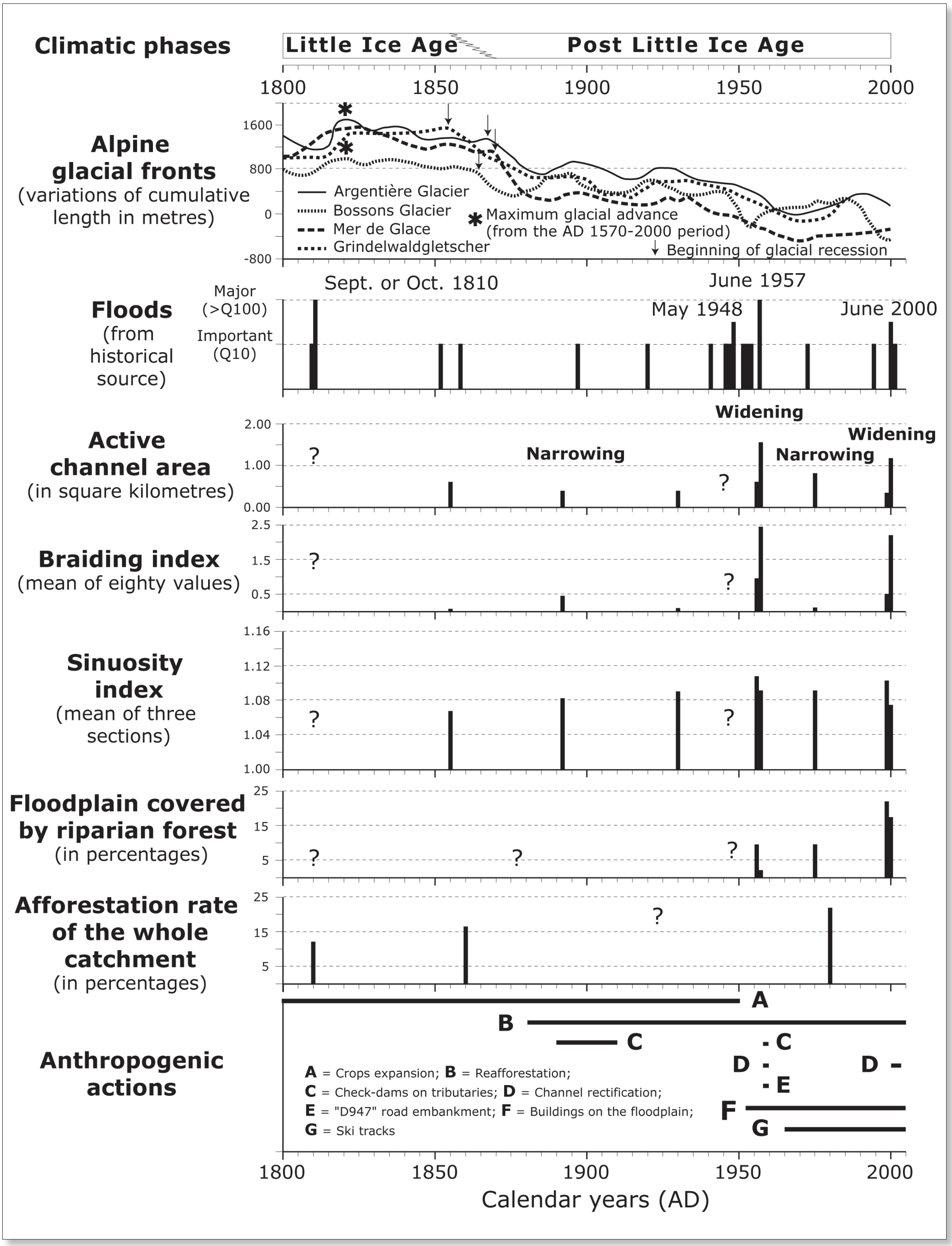

Fig. 12 – Synthesis of the recent evolution of the Upper-Guil active channel *vs.* the climatic and human control factors. Note that the 1957 and 2000 floods were triggered by heavy rainstorms, and aggravated in 1957 by late spring snow melt.

The structure was built into the limits of the 1957 flood and reduced the width of the active channel by 28% compared to 1957. This is as a result of significant channel narrowing but it does not completely explain the phenomenon.

The other important factor is the fact that the Upper Guil valley was not affected by LFHM hydro-climatic events during this period, except that of the spring of 1973, with a magnitude well below those of 1957 or 2000.

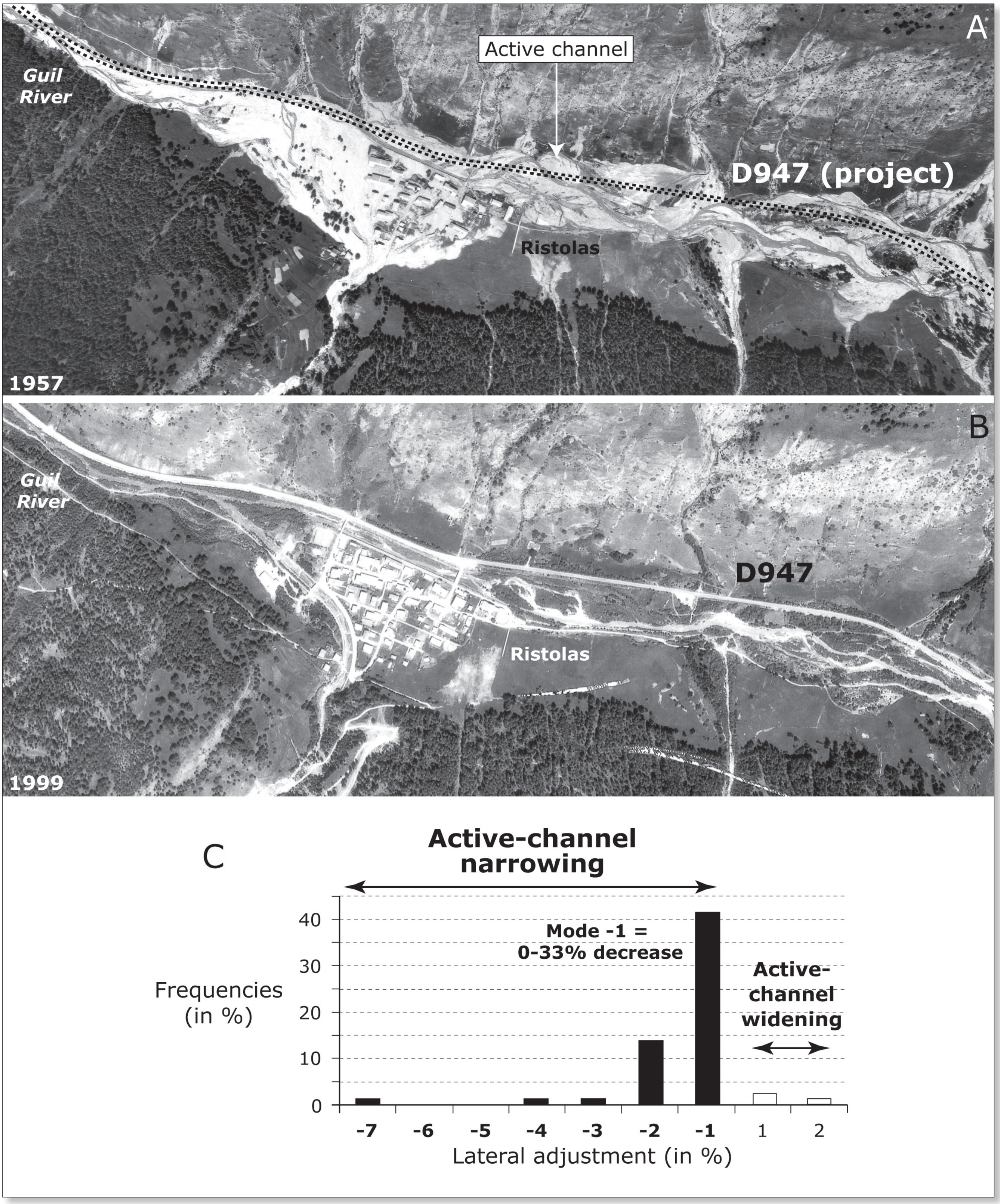

Fig. 13 – Narrowing of the Upper-Guil active channel between 1957 and 1999. (A) and (B) Impact of the D947 road embankment (photos: IGN). (C) Width adjustment of the Upper-Guil floodplain following the completion of the D947 road embankment in 1957 (quantification deduced from a 23 km-long survey). Negative values represent the reduction of the active-channel width, positive values correspond to the increase of the active-channel width. The active channel has most often narrowed from 0 to 33% compared to 1957 (mode -1: 42%); -7: narrowing by 75.00-77.78% (/4-4.5); -6: narrowing by 71.43-75.00% (/3.5-4); -5: narrowing by 66.67-71.43% (/3-3.5); -4: narrowing by 60.00-66.67% (/2.5-3); -3: narrowing by 50.00-60.00% (/2-2.5); -2: narrowing by 33.33-50.00% (/1.5-2); -1: narrowing by 0.00-33.33% (/1-1.5); 1: widening by 0-50% (x1-1.5); 2: widening by 50-100% (x1.5-2).

We must therefore take into account these two factors (*i.e.*, absence of large floods, artificial disconnection of a large part of the flood plain) to explain the narrowing of the active channel between 1957 and 1999. Recolonisation of the valley bottom by vegetation was able to operate and act as an aggravating factor forcing the active-channel narrowing. Upon the terraces derived from the incision of the 1957 flood deposits, we have shown that the mean age of the riparian forest was 45 years in 2013, indicating that the forest recovery begun 11 years after the deposits

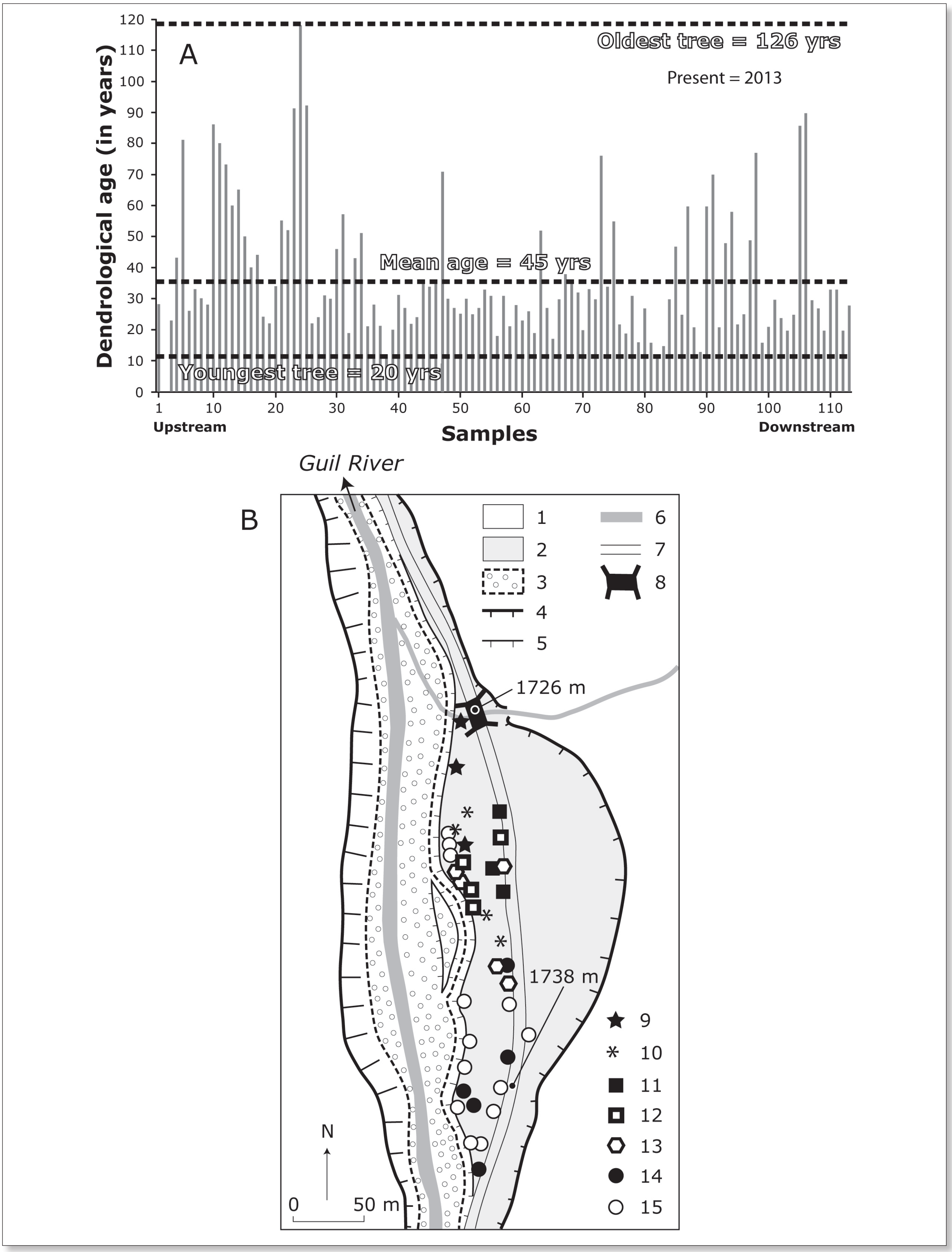

Fig. 14 – Dendrochronological results. (A) Downstream distribution of larch tree ages (103 samples) on the 1957 terrace of the Upper Guil River. The ages of the trees range from 20 to 126 years, for a mean age of 45 years (reference year: 2013). Note that larch tree re-growth may take up to 10 years after a flood event. (B) Local downstream dendro-chronological gradient on the site upstream from L'Échalp. The oldest trees are located on the downstream part of the 1957 terrace. Upstream, the terrace tends to be reactived by floods (including that of 2000), thus regenerating the riparian forest. The latter in turn tends to attenuate the flood power. 1: slope; 2: 1957 alluvial terrace; 3: 2000 active channel; 4: valley bottom limits; 5: scarp; 6: Guil channel; 7: D947 road; 8: bridge; 9: tree ages varying between 75 and 120 years; 10: tree ages varying between 65 and 75 years; 11: tree ages varying between 55 and 65 years; 12: tree ages varying between 45 and 55 years; 13: tree ages varying between 35 and 45 years; 14: tree ages varying between 25 and 35 years; 15: tree ages varying between 15 and 25 years.

of the 1957 flood, in agreement with biological studies (fig. 14). This delay is caused by new edaphic conditions imposed after a flood event. Our work also shows that there is a downstream dendro-chronological gradient, the oldest trees being located in the downstream part of the 1957 terrace, the upstream part being exposed to more recurrent erosion and more frequent renewal of the forest. There is indeed a biological control on channel widening/ narrowing but it depends on hydraulic conditions on the floodplain.

5.3 - Hydro-climatic variability: a critical impact

LFHM floods play a key role in the lateral dynamics of the active channel and more widely on valley-bottom morphogenesis. This has been demonstrated twice in 150 years, during the floods of 1957 and 2000 (fig. 12). The hydro-geomorphological impact of LFHM floods is generally proportional to the magnitude of the hazard. Thus, the 1957 flood was generally more morphogeneous than the 2000 flood.

However, the 2000 flood, although it did not reach the record discharge of the 1957 flood, still represents the hazard that led to the greatest variation of the active-channel area (+240% between 1999 and 2000 compared to +165% between 1956 and 1957). This result is indeed speculative because, unlike the hydrological context in 2000, the 1957 flood occurred after the Guil active channel was widened a few years before (between 1941 and 1954) by several flood events of moderate magnitude, including the 1948 flood as shown in figs. 9 and 12 (active-channel area). Nevertheless, compared to the 1957 flood, the 2000 flood was more morphogeneous in the upstream part of the Upper Guil valley. This is confirmed by the braiding index that, in 2000, exceeded that of 1957,

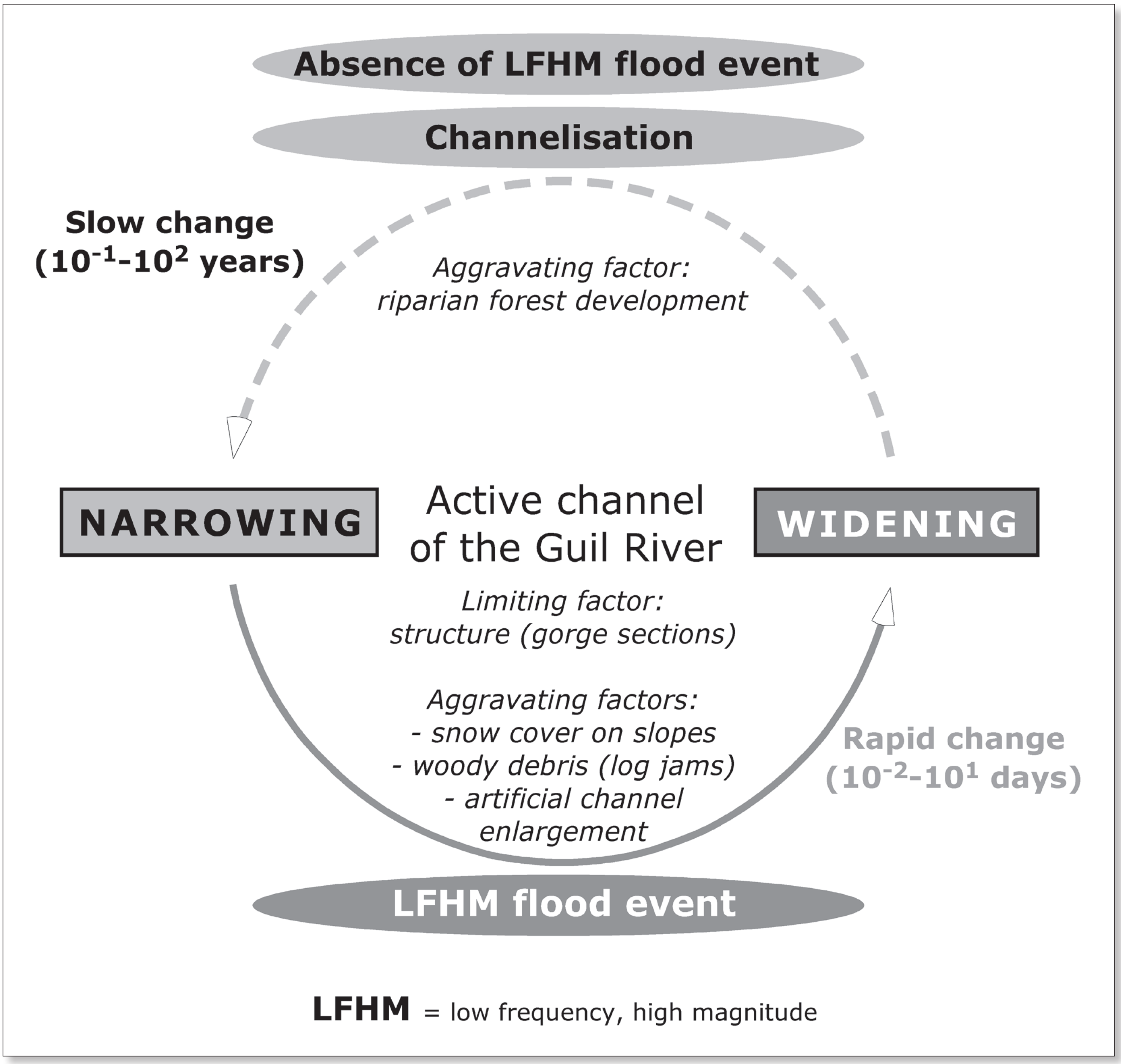

Fig. 15 – Hydro-bio-morphological modelling of the Upper-Guil active channel. In the braided sections (the gravel bars in particular), there is no vegetation cover.

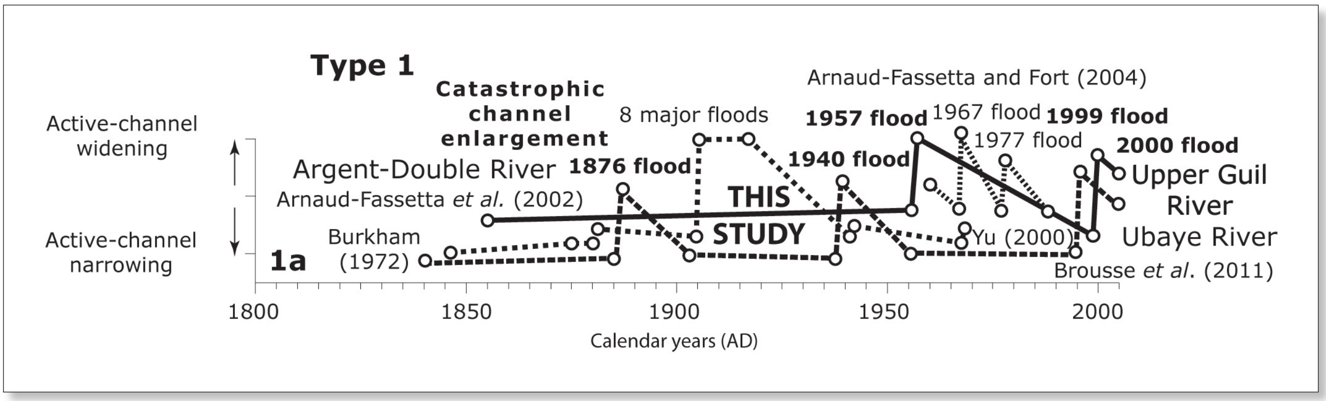

Fig. 16 – The Upper Guil River: its hydromorphological behaviour is largely influenced by the occurrence of LFHM floods that allows to complementing the floodplain typology (Type 1a; see also fig. 1).

and by the width variations of the active channel between 1957 and 2000, generally positive and of higher amplitude in the upstream part of the catchment. Several factors explain this situation: (i) the presence in 2000 of rainfall cells centred on the upstream part of the catchment, (ii) in June 2000 the limited extension of the snow cover even in the the upstream catchment, while in June 1957 the snow was still very abundant (TRICART, 1958), and (iii) a lower lateral constraint in 2000, due to alluvial cones which were more poorly developed compared to 1957. Downstream of L'Échalp, some areas were widened in 2000, so that the limit of the active channel could, at least locally, slightly exceed that of 1957. This was the case in the Praynas plain between the Ribes plain and Aiguilles plain (ARNAUD-FASSETTA *et al.*, 2005). These local forms of active-channel widening express the need for the Upper Guil River to dissipate its energy and power in the areas of lower gradient (*i.e.*, mainly in the plains).

The areas where the limits of the 1957 flood were exceeded in 2000 can thus be explained by the effects of the reduction (on the site and/or upstream) of the areas of natural flood dissipation, due to the implementation of D947 road embankment and reduced channel sinuosity. Valley-bottom morphogenesis is primarily linked to the magnitude of the hydro-climatic hazard, but the human and vegetation factors can mitigate or enhance the effects (fig. 15).

6 - Conclusions

A scientific approach based on archives, alluvial stratigraphy, photo-interpretation and torrential hydraulics, has shown that the Upper Guil functioning is different from what is generally described in the Prealps. Since the final part of the LIA (AD 1855), the active channel of the Upper Guil River experienced an alternation of short phases of widening and braiding, related to the occurrence of LFHM floods (those of 1957 and 2000 in particular), and of longer phases of narrowing during which forest recolonisation of the valley bottom was accompanied by a reduction in braiding (fig. 16). This thesis therefore mitigates the role played by human actions, considered as aggravating or attenuating hydro-climatic variability. Despite the significant impact of anthropogenic activities during the considered period, climatic variability seems to remain the critical control parameter of the hydromorphodynamic functioning of the Guil valley, because of the predominant influence of its main tributaries.

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