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Hydro-geomorphic hazards and impact of man-made structures during the catastrophic flood of June 2000 in the Upper Guil catchment (Queyras, Southern French Alps)

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Abstract

The Guil River Valley (Queyras, Southern French Alps) is prone to catastrophic floods, as the long historical archives and Holocene sedimentary records demonstrate. In June 2000, the upper part of this valley was affected by a "30-year" recurrence interval (R.I.) flood. Although of lower magnitude and somewhat different nature from that of 1957 (>100-year R.I. flood), the 2000 event induced serious damage to infrastructure and buildings on the valley floor. Use of methods including high-resolution aerial photography, multi-date mapping, hydraulic calculations and field observations made possible the characterisation of the geomorphic impacts on the Guil River and its tributaries. The total rainfall (260 mm in four days) and maximum hourly intensity (17.3 mm h^{-1}), aggravated by pre-existing saturated soils, explain the immediate response of the fluvial system and the subsequent destabilisation of slopes. Abundant water and sediment supply (landsliding, bank erosion), particularly from small catchment basins cut into slaty, schist bedrock, resulted in destructive pulses of debris flow and hyperconcentrated flows. The specific stream power of the Guil and its tributaries was greater than the critical stream power, thus explaining the abundant sediment transport. The Guil discharge was estimated as 180 m^3 s^{-1} at Aiguilles, compared to the annual mean discharge of 6 m^3 s^{-1} and a June mean discharge of 18 m^3 s^{-1}. The impacts on the Guil valley floor (flooding, aggradation, generalised bank erosion and changes in the river pattern) were widespread and locally influenced by variations in the floodplain slope and/or channel geometry. The stream partially reoccupied former channels abandoned or modified in their geometry by various structures built during the last four decades, as exemplified by the Aiguilles case study, where the worst damage took place. A comparative study of the geomorphic consequences of both the 1957 and 2000 floods shows that, despite their poor maintenance, the flood control structures built after the 1957 event were relatively efficient, in contrast to unprotected places. The comparison also demonstrates the role of land-use changes (conversion from traditional agro-pastoral life to a ski/hiking-based economy, construction of various structures) in reducing the Guil channel capacity and, more generally, in increasing the vulnerability of the human installations. The efficiency of the measures taken after the 2000 flood (narrowing and digging out of the channel) is also assessed. Final evaluation suggests that, in such high mountainous environments, there is a need to keep

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most of the 1957 flooded zone clear of buildings and other structures (aside from the existing villages and structures of particular economic interest), in order to enable the river to migrate freely and to adjust to exceptional hydro-geomorphic conditions without causing major damage.

Keywords: Fluvial geomorphology; Extreme flood; Hydro-geomorphic impact; River basin management; Guil River; Southern French Alps

1. Introduction

Unglaciated Mediterranean or sub-Mediterranean mountains are frequently subject to hydro-climatic events resulting in ephemeral, flash floods (Harvey, 1984; Gallart and Clotet-Perarnau, 1988; Ballandras, 1993; Macklin et al., 1995; White et al., 1997; Poesen and Hooke, 1997; Guttiérez et al., 1998; Maas and Macklin, 2002). These are rather common, being related to typical meteorological situations in which warm, humid air masses formed above the Mediterranean Sea, are cooled by uplift over the adjacent landmass, releasing intense rainfall. Such events are not unexpected by the local population, who are well aware of the potential dangers related to a rapid rise of water levels in the river channels. For this reason, villages are generally sited on elevated spurs or ridges, foot slopes or edges of tributary torrential fans, as places considered relatively safe from flood risk. However, some floods are more intense than others and, through the important amount of geomorphic work they can accomplish in a very short time, they may be a source of significant damage and serious loss to human infrastructures.

In the upper valleys, the high altitude environment may create specific flood conditions in relation to a higher runoff concentration and the abundant production of debris. The Guil River (Hautes-Alpes, France) drains a valley that is representative of the catastrophic floods that occur in the southern French Alps. Though mostly influenced by humid air masses from the Atlantic, this area is occasionally subject to storms derived from humid Mediterranean air masses, as the origin of such floods. The most documented catastrophic flood occurred in June 1957. It consisted of an exceptional, low-frequency (more than 100-year recurrence interval, R.I.), high-magnitude hydro-geomorphic event, which also affected the adjacent Ubaye, Cerveyrette and Maurienne valleys. The effects of this event were thoroughly analysed by Tricart (1958, 1961a,b). The damage associated with the 1957 flood was such (~15 million euros) that the French Government took important measures to repair destroyed structures, and built at considerable cost new protective structures (embankments, canals, dikes) where, and only where, it was considered that people and/or buildings were potentially under threat. These measures remained the only flood control structures in the Guil hydro-system in 2000. In fact, the 1957 flood is considered to be the reference flood used in hydraulic models and/or management planning in the Guil Valley (Parc Naturel Régional du Queyras, 2002).

In June 2000, the Upper Guil Valley was again affected by a major, 30-year R.I. hydro-geomorphic event. Although of lower magnitude and of a somewhat different nature from that of 1957, this recent flood caused serious damage to infrastructure and buildings along the valley floor (~4.6 million euros), because of the many land-use changes (conversion from traditional agro-pastoral life to a ski/hiking-based economy, construction of various structures) that have taken place during the past four decades. The aims of the present study are as follows: (1) to document the geomorphic and hydrological characteristics of the June 2000 flood; (2) to compare the impacts of the 30-year R.I. June 2000 flood with those of the >100-year R.I. 1957 flood in the context of land-use change; (3) to assess the efficiency of the flood control structures built after 1957 against recent land-use changes; and finally (4) to suggest some recommendations bearing upon river management. In this study, particular attention is accorded to Aiguilles village and its surroundings, given that it was the most severely affected area. Following a description of the main characteristics of the Guil catchment, the characteristics of the June 2000 event and its impact upon both the tributaries and the main Guil Valley are set out. Finally, the different factors that contributed to material losses greater than those generated in 1957 are evaluated.

2. The Guil catchment: an area prone to catastrophic floods

Located in the southern French Alps, adjacent to the Italian border northwest of Mt. Viso (3841 m), the Guil River, a left bank tributary of the Durance River, drains a 730-km^2 catchment (Fig. 1). Elevations range from 897 m to over 3300 m.

This paper focuses on the Upper Guil catchment (317 km^2), upstream of Château-Queyras. From the Italian border down to the Roche Ecroulée (1780 m), the Guil River is a steep mountain stream, with an average slope of 15% (varying between 58% and 4–5%). Downstream the Roche Ecroulée, the slope progressively decreases from 6% to 1.8% (Château-Queyras) and becomes more regular, whereas the valley widens, with a few narrower and steeper sections (downstream of Ristolas; Preyt gorges upstream of Aiguilles; gorges upstream of Ville-Vieille). The slope of the main tributaries (Ségure, Peynin) is steeper (17–20% on average), varying between 10% and 50%. The geomorphic attributes of the Guil catchment can be considered as representative of this part of the Alps, and are dominated (1) by snow avalanches, the major transporting agent for sediment from slopes to talwegs, and (2) by river incision, transfer and aggradation. In addition, infrequent, yet destructive torrential floods may occur. Several predisposing factors (climate, topography, lithostructural context) explain the recurrent torrential flow events and the resulting difficulty for local managers, who also have to cope with the legislation and management procedures of the Parc Naturel Régional du Queyras (PNRQ). The permanent population does not exceed 1000 inhabitants, but during the peak tourist season, the resident population can approach 6000. Owing to the scarcity of land suitable for building, the pressure on land on the lower slopes has increased progressively during the past few decades, and has led to a notable amount of construction on the flat, vulnerable floodplain of the Guil River. Major villages are Ristolas (1604 m; 78 inhabitants), Abriès (1536 m; 354 residents), Aiguilles (1456 m; 441 inhabitants), and Ville-Vieille/Château-Queyras (1379 m/1328 m; 350 people).

2.1. Physical setting

The torrential nature of the drainage in this unglaciated sub-Mediterranean mountain area is chiefly controlled by the climatic and lithostructural characteristics of the catchment.

The Guil Valley belongs to the inner part of the western Alps, influenced to some degree by continentality. Mean annual precipitation is 828 mm in Abriès and 714 mm in Château-Queyras. Snowfall predominates in the valley bottom during winter, whereas storms, partly related to northward transgressions of Mediterranean air masses, can result in substantial rainfalls within a short time. More specifically, in some meteorological situations known as the “Lombarde” type, the existence of perturbations centred above the Gulf of Genoa favours the advection of humid air masses northwards; when these reach the Alps, they are vigorously uplifted, causing both frontal and orographic rains. Such events occur mostly during late spring or early autumn. Their effect is at a maximum in the vicinity of Mt. Viso and along the surrounding mountain crest lines.

The hydrographic network has a generally rectangular pattern (sensu Howard, 1967), partly controlled by the underlying substratum (general west–northwest dip of the Alpine thrust sheets). With an average relief not exceeding 1500 m, the Upper Guil Valley is characterised by asymmetrical structural slopes related to the late Alpine reverse folding of the Pennine nappes (Lemoine and Tricart, 1988). Gentle dip slopes, generally deforested, are covered by a regolithic mantle and are subject to superficial translational landslides. These contrast with the steep, rocky, northeast to southeast facing counterdip slopes, covered by larch forests and densely dissected by mixed avalanche/torrent tracks (>50% slope), forming small, first-order catchments with areas of less than 1 km^2; these are prone to accelerated runoff and a short hydro-geomorphic response time following intense rainfall.

The lithological context of the Upper Guil Valley corresponds to the “schistes lustrés” belt of the inner Alps, in which olistolites of ophiolitic rocks are included. The schists, representing 90–95% of the total outcrops, may vary locally in their facies (sandstones, calcschists), but generally have the form of impervious, tectonised, frost-sensitive bedrock. Easily shattered, the schists supply abundant, flattened

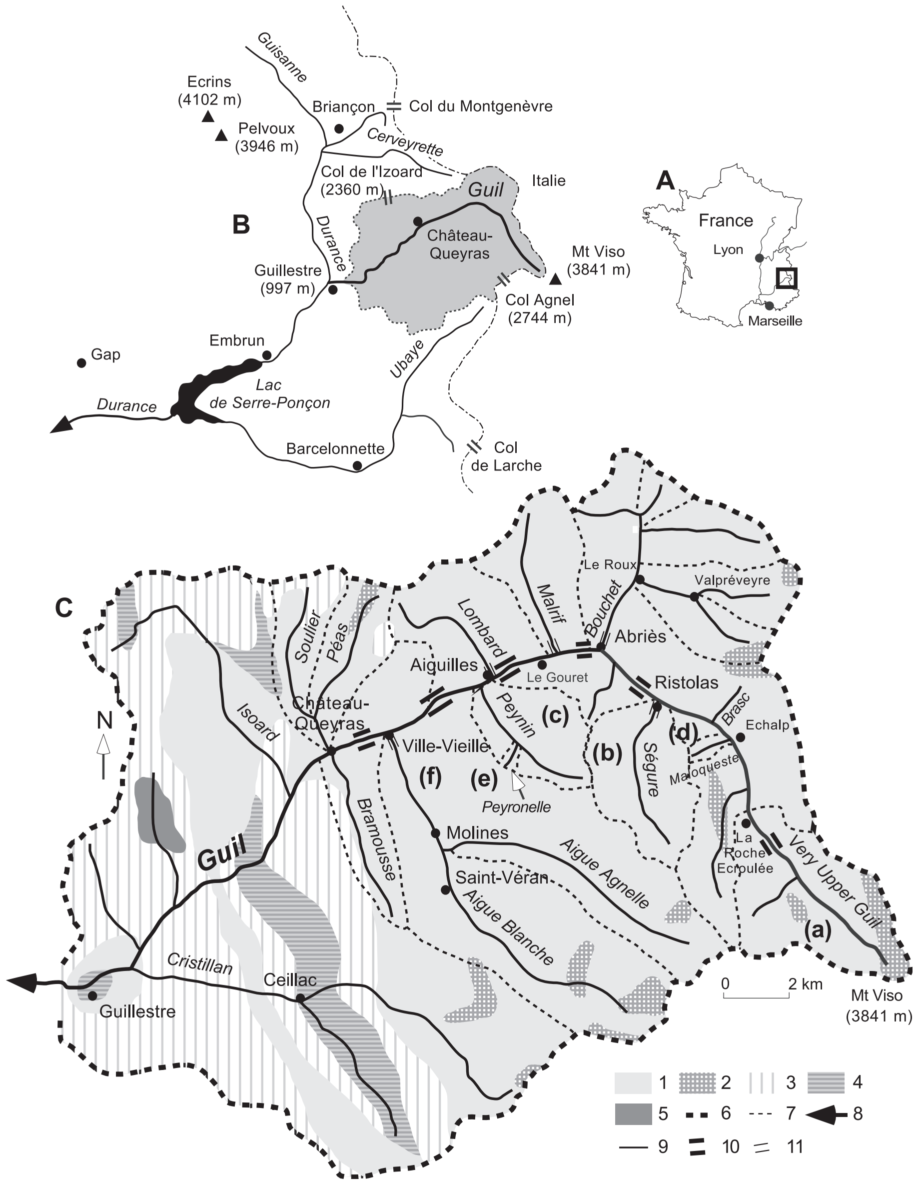


Fig. 1. The Guil River catchment. (A) General location and (B) location of the Guil basin in the Durance catchment. (C) The study site corresponds to the part located upstream Château-Queyras. Lithology: 1=schists “lustrés”; 2=ophiolite complex; 3=limestones and dolomites; 4=sandstones and conglomerates; 5=flyschs. Hydrography: 6=limit of the Guil catchment (317 km^2 upstream Château-Queyras); 7=subcatchment divides (a=26 km^2, b=16 km^2, c=15 km^2, d=0.94 km^2, e=0.41 km^2, f=98 km^2); 8=Guil River; 9=main tributaries of the Guil River; 10=gorge section; 11=channelised stream.

debris, among which silts and phyllitic minerals (called “nite” in the local idiom) play an important role in the torrential flow modalities. In fact, their abundance favours, during any single event, rapid transition from torrential flow to supersaturated flow and eventually to debris flow, capable of mobilising very large boulders.

In sum, the Upper Guil catchment offers a combination of characteristics that favour strong torrential activity; these include sudden, abundant and intense rain falling on steep slopes that have been dissected into small subcatchments in which accelerated runoff and a short response time trigger flash-flood events.

2.2. A long record of catastrophic floods

Historical records mention several important events, which variously affected different parts of the Upper Guil Valley (Table 1). Some of them were of a quite local extent, mostly at the confluence of the Guil River and its tributaries. Others were more widespread affecting the whole valley including all the villages of Queyras. Houses, churches and graveyards have been flooded, and much agricultural land, and many mills and trails were washed away in events dating from 1408, 1431, 1791, 1810, 1948 and 1957 [Restauration des Terrains en Montagne (RTM archives); Tivollier and Isnel, 1938; Tricart, 1958; Fanthou, 1994].

Table 1
Records of historical floods in the Upper Guil Valley (upstream of Château-Queyras)

Year[a]	Month/day	Streams affected by flooding[b]	Localities affected by flood hazard[c]	Sources[d]
2002	July 15–16	GU, SE, BO, AA	ECH, GOU	9
2000	October 13–15	GU, BO	RIS, ABR, LER, AIG, CVV	9; 10
2000	June 10–14	GU, BO, PE, AA	ECH, RIS, ABR, LER, AIG, CVV	9; 10
1994	June 26	AA	CVV	1
1973	Spring	AA	Upstream of VV	4
1957	June 13–15	GU, SE, BO, LO, PE, AA	RIS, ABR, LER, AIG, CVV	1; 3
1954	August 21	BR	CVV	1
1953	September 29	GU	AIG	1
1953	June 8	GU, PE	AIG	1
1952	July 24	BR	CVV	1
1948	May 12–15	GU, BO	ABR, LER, AIG, CVV	1; 3
1947	August 12	BR	CVV	1
1946	August 29	BR	CVV	1
1941	June 22	BR	CVV	1
1920	September 19–25	GU	ABR	3
1897	July	GU	AIG	7
1858	–	GU	–	2
1852	August 5	AA	CVV	1
1810	September or October 13	GU and its tributaries	RIS, ABR, AIG, CVV	1; 2; 7; 11
1810	January 16	GU	ECH, RIS	1; 7
1791	October 9–11	GU and its tributaries	RIS, ABR, AIG	1; 3
1788	September 7	GU	AIG, CVV	1
1739	December 3–5	AA	–	3; 11
1728	May 19–21	GU, LO	ABR, AIG, CVV	1; 2; 3
1704	–	LO	AIG	1
1651	January 10–14	AA	MOL	3; 11
1469	May 23	GU, SE	RIS	3; 11
1431	June 4–24	GU, SE, BO, LO	RIS, ABR, AIG, CVV	1; 2; 5
1419	–	GU	AIG, CVV	1
1412	–	GU	AIG, CVV	1
1409	–	GU	AIG, CVV	1; 2
1408	–	GU, SE, BO, LO	RIS, ABR, AIG, CVV	1; 2
1370	–	GU	CVV	2; 6
1332	–	GU	CVV	2; 6; 8

[a] Bold values correspond to large flood events.
[b] GU=Guil; SE=Ségure; BO=Bouchet; LO=Lombard; PE=Peynin; AA=Aigue Agnelle; BR=Brasc.
[c] ECH=Echalp; RIS=Ristolas; ABR=Abriès; LER=Le Roux; GOU=Le Gouret; AIG=Aiguilles; CVV=Château-Ville-Vieille; VV=Ville-Vieille; MOL=Molines.
[d] 1=RTM Archives; 2=Tivollier and Isnel, 1938; 3=Tricart, 1958; 4=Tricart, 1974; 5=Lapeyre and Lapeyre, 1982; 6=Lemoine and Tricart, 1988; 7=SOGREAH Archives; 8=Fanthou, 1994; 9=PNRQ; 10=Fort et al., 2002; 11=Chaillet, 2002.

Also, various artefacts clearly indicate a high level of concern about the flood menace within the village communities. At Abriès for instance, a carved stone, dating from about 1768, was discovered emplaced at the top of an embankment bordering the Bouchet stream, probably having been set there in order to protect the village from future floods (M. Blanchet, oral communication). Similarly, many chapels (Château-Queyras, Valpréveyre) have been erected in the past to obtain divine protection against floods.

Holocene sedimentary and other records (fossil tree-trunks) of prehistoric floods also provide good evidence of recurrent torrential activity at least during the last 4000 years (Fort et al., 2002). The presence of very thick coarse deposits, cut-and-filled by the 1957 or 2000 deposits, reflects the existence of episodes of catchment destabilisation related to detritic crisis (the "crises détritiques" of Jorda, 1985). The oldest torrential deposits, radiocarbon dated to 2839–2473 cal. B.C. and 95–319 cal. A.D., are in fairly good agreement with what is now known of the Holocene evolution of the southern Alps (Ballandras, 2002).

2.3. The June 1957 flood

The June 1957 flood (>100-year R.I.), considered as the reference flood of the Upper Queyras district, led to the development of extensive flood control management works. Before the flood, the valley bottom was drained by the single-thread channel of the Guil River, which cut into a wide, gravelly and sandy floodplain, covered by a riparian woodland (in which larch-trees were predominant) or occupied by pastures and hay meadows. During the flood, the entire valley bottom was affected, and the lower slopes were undermined by lateral cutting, which

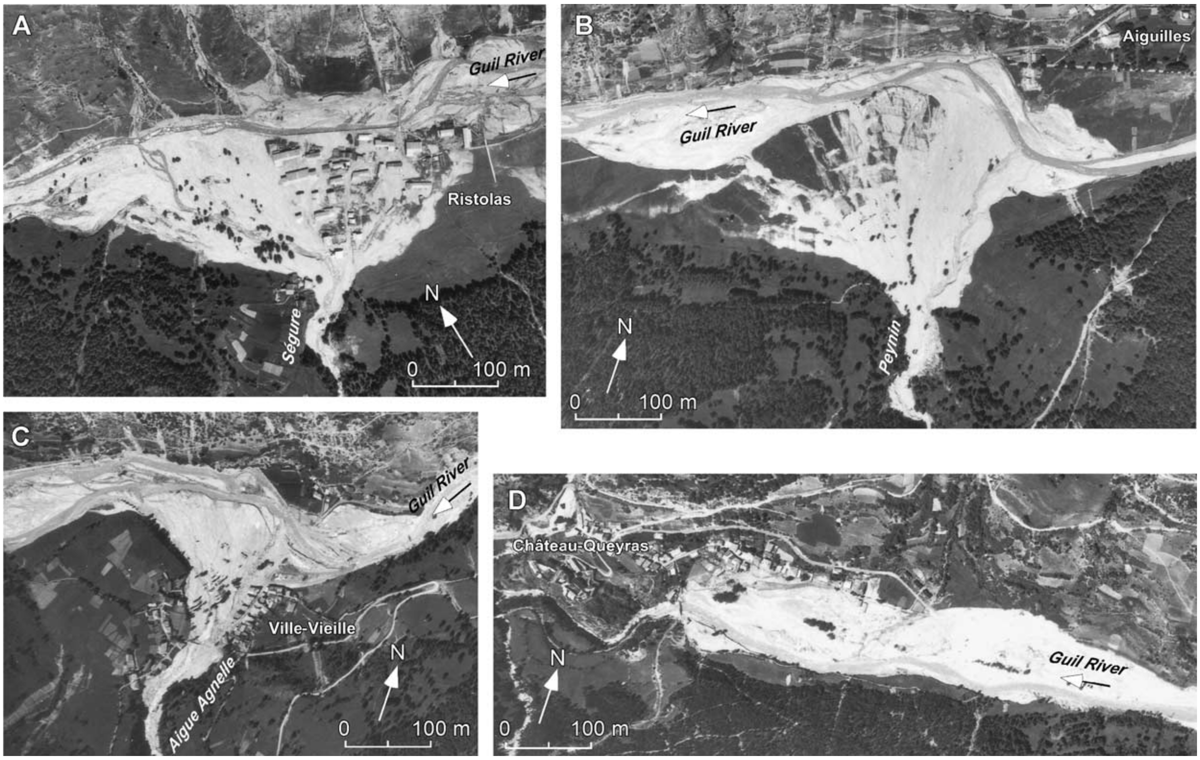


Fig. 2. Selected sites displaying the impacts of the 1957 flood at the main confluences between the Guil River and its tributaries. Note sediment accumulation on alluvial fans and channel widening along the Guil River, occupying its entire floodplain. (A) Guil/Ségure confluence, Ristolas fan (1604 m); (B) Guil/Peynin confluence, downstream of Aiguilles (1456 m); (C) Guil/Aigue-Agnelle confluence, Ville-Vieille (1379 m); (D) Château-Queyras, damming effect upstream the gorges cut into the rocky glacial knob of Château-Queyras (1328 m) (IGN aerial photographs).

triggered landslides and provided huge quantities of material to the valley bottom. Many log jams accumulated at the narrow sections; these effectively dammed the river for a while until outburst flood-waves occurred, which, in some places, were powerful enough to move very large boulders (Tricart, 1961a, referred to ophiolitic green boulders, 2-m long and exceeding 10–15 tons in weight at Ville-Vieille). The peak discharge probably reached 315 m^3 s^{-1} at Aiguilles (Koulinski and Lefort, 2000). Many parcels of land were washed away; for instance, in Aiguilles, about 50 ha of crops and meadows were lost and 500 m^3 of woodland was destroyed (RTM). Strong sediment depositions were observed on alluvial fans of the Guil tributaries (Fig. 2). In the Château-Queyras area, the Guil floodplain was entirely flooded. A temporary lake was formed after the obstruction of the gorges and considerable aggradation was observed (estimates >1,000,000 m^3; Tricart, 1961a) (Fig. 2D).

Some management structures existed before 1957, some probably dating from as early as the 15th century. At Ristolas for instance, the inhabitants built two large wooden dikes after the 1419 flood (Tivollier and Isnel, 1938); according to archives (RTM), some embankments were destroyed at Aiguilles during the 1791 flood. Whatever the nature of these old protective structures, they were in no way comparable in size and extent to those built after 1957. In fact, after the 1957 disaster, the French Government provided special funds to enhance flood control structures along many torrential rivers (i.e., not only the Guil, but also the Ubaye, the Cerveyrette, and the Arc rivers) that had been affected by the 1957 event. Many heavy and costly structures were emplaced. The Upper Guil tributaries, the Ségure, the Bouchet, the Malrif, the Lombard and the Aigue Blanche were channelised in their torrential fans with weirs, whereas their longitudinal profile was partly corrected by check-dams in their upstream gorges (Ségure, Lombard). The Guil River itself was locally channelised, with various types of protection (dykes, gabions, stony walls and/or concrete retaining walls, bed armouring), or confined by embankments also used for road foundations. However, these protective measures were not continuous, being limited to those fluvial segments with the greatest vulnerability, where losses had occurred (i.e., in the villages). In contrast, many other areas where there was no human or material stake to protect (i.e., floodplain bordered with riparian forest) were left unmanaged. This was the situation prevailing nearly 50 years later, when the 2000 30-year R.I. flood again affected the Upper Queyras.

3. Materials and methods

3.1. Photo-interpretation

In order to compare the respective impacts of the June 1957 and June 2000 floods, we analysed several sets of air photos for different dates, before and after the floods, namely: June–July 1956 (IGN; A23/3537–3697; 1/25,000 scale), June–July 1957 (IGN; FR-086/150; 1/15,000 scale), June 9–22, 1999 (IGN; FD05/250; 1/25,000 scale), June 16, 2000 (RTM; AERIAL 08-00.1266/732; 1/8,000 scale). Scanning and geometric rectification of photographs were first performed. Photo analysis was then carried out in two ways, firstly for specific site studies and geomorphological mapping, secondly for systematic analysis of the effect of the floods on active channel width and, of the impact of engineering works on the channel response. Eighty sites were selected at regular intervals (every 250–300 m) along the river course. The total length studied amounts to 23 km, which corresponds to the entire Upper Guil River with the exception of the first 5 km, not photographed in 1957. We measured the "active channel width" (Osterkamp and Hedman, 1982), the portion of the alluvial landscape composed of active, unvegetated gravel bars and low-flow channel(s) as defined by Rundle (1985). The compared measurements of active channel width from aerial photos and the field give a very good correlation between the two methods (Fig. 3).

3.2. Field survey procedures

Field observations were carried out before (May 1999, May 2000) and after (July 2000, May and July 2001, May, July and September 2002) the 30-year R.I. flood of June 2000. They include a geomorphological survey at a 1/6000 scale, and the mapping of morphological change of bed width and channel slopes. We tried to quantify the volumes of eroded

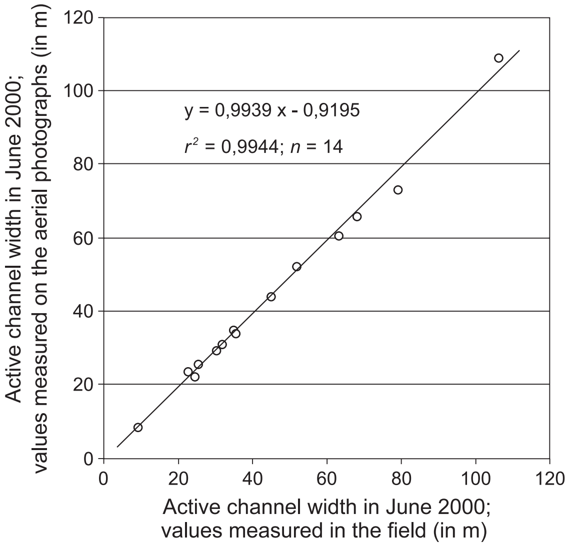


Fig. 3. Correlation between measurements of the active channel width deduced from field surveys and from aerial photograph measurements.

material (bank cutting, slope failure and landsliding) and aggraded material (gravel bars and sheets on fans or within active channels). Eroded and aggraded volumes were measured by using an electronic distance device. Aggraded volumes on the fans were calculated by reconstructing the 3D geometry of gravel sheets, the depth of which was estimated from the pre-2000 "reference" surface, as displayed on sections along the gullies and/or channels cut through the gravel sheets at the end of or immediately after the event. Reference surface is identified by the presence of organic debris (buried vegetation) and soil development. The areal extent of the aggradations was calculated both from the field and from aerial photos. We applied the following equation:

$$V_A = S_A T_A - V_E \qquad (1)$$

where V_A=total volume of sediment accumulated on the alluvial fan (in m^3), S_A=surface of active alluvial fan (in m^2), T_A=mean thickness of sediment layer (in m) and V_E=entrenchment of active alluvial fan by channels (volume in m^3).

Channel cross-sectional areas were surveyed along the Guil River (n=32, from the source to Château-Queyras) and its tributaries (n=19, Ségure; n=19, Peynin) during summer 2001. These cross-sections were surveyed perpendicular to the assumed flow direction of the main channels, by using standard field techniques (level, rangefinder, pocket rod), as indicated by Thorne (1998).

3.3. Characterisation of bed-material grain size

Sediments have been collected at each cross section. For the gravel material, Church et al. (1987) recommended that the weight of the coarsest particle not exceed 1% of 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 (Wolman, 1954; Folk, 1980; Thorne, 1998). For grain-size characterisation, the >5-mm fraction was analysed in situ using a pocket rod to measure the longest axis of each particle. The <5-mm fraction was analysed using the dry-sieving technique (AFNOR standard). For each sample, grain-size data were characterised by computing D_{30}, D_{50} and D_{90}, which correspond to particle diameters for which 30%, 50% and 90% are finer, respectively. As indicated by Doyle and Shields (2000), D_{50} best represents the grain-size distribution. The three percentiles cited above were used in several hydraulic calculations.

3.4. Hydraulic calculations

Several hydraulic parameters (stream power, bed shear stress, transport capacity) were calculated in order to quantify hydrodynamic characteristics and bed-material volume of the Guil River and its tributaries during the flood of June 2000.

The unit stream power (ω) has been calculated using the Bagnold (1980) equation:

$$\omega\left(Wm^{-2}\right) = (\rho_w g Q S) W^{-1} \qquad (2)$$

where ρ_w is water density (kg m^{-3}), g is gravitational acceleration (m s^{-2}), Q is discharge (m^3 s^{-1}), S is slope (m m^{-1}), and W is active channel width (m). In the absence of available data at each study site, Q in Eq. (1) has been estimated from the equation in Rotnicki (1991):

$$Q = \left(0.921 n^{-1}\right) A R^{0.67} S^{0.5} + 2.362 \qquad (3)$$

where n is Manning's resistance coefficient, A is cross-sectional area (m^2), and R is hydraulic radius (m). The

Jarrett (1985) equation was used to determine an initial value of n in Eq. (3):

$$n = 0.32S^{0.38}R^{-0.16} \tag{4}$$

The critical stream power (ω_{cr}) has been defined by the Costa (1983) equation:

$$\omega_{cr}\left(\mathrm{W\ m^{-2}}\right) = 0.009D_{50}^{1.686} \tag{5}$$

where D_{50} is median bed-material grain size (mm), and by the Bagnold (1980) equation, expressed in Martin and Church (2000) as:

$$\omega_{cr}\left(\mathrm{W\ m^{-2}}\right) = 5.75[0.04(\gamma_s - \gamma_w)\rho_w]^{3/2}\left(g\rho_w^{-1}\right)^{1/2}D^{3/2}\log\left(12dD^{-1}\right) \tag{6}$$

where γ_s is specific gravity of sediment and γ_w is specific gravity of water.

Moreover, mean boundary shear stress (τ) exerted by the fluid on the riverbed has been calculated using the relation of Du Boys (1879):

$$\tau = \rho_w gRS$$

The critical shear stress (τ_{cr}) needed to initiate movement depends principally on grain size, according to the equation of Lane (1953):

$$\tau_{cr}\left(\mathrm{N\ m^{-2}}\right) \simeq D \tag{7}$$

where D is characteristic particle size (cm), and to the equation of Costa (1983):

$$\tau_{cr}\left(\mathrm{Nm^{-2}}\right) = 0.056D_{50}^{1.213} \tag{8}$$

Also, in the absence of direct measurements of bed-material transport, an alternative method of estimating bed-material transport was required (Gilvear and Bradley, 1997; Ham and Church, 2000). Bathurst et al. (1987), followed by Gomez and Church (1989), concluded that the Schoklitsch (1962) equation performs best when predicting the bed-material transport capacity in gravel-bed channels. This equation is defined as:

$$q_{ub}\left(\mathrm{m^2 s^{-1}}\right) = \left[2.5\left(\rho_s\rho_w^{-1}\right)^{-1}\right]S^{1.5}\left[\left(QW^{-1}\right) - q_{cru}\right] \tag{9}$$

where q_{ub} is bed-material discharge per unit width ($\mathrm{m^2\ s^{-1}}$), ρ_s is sediment density ($\mathrm{kg\ m^{-3}}$), and q_{cru} is critical water discharge per unit width for the particle size D_{50}, defined as:

$$q_{cru}\left(\mathrm{m^2\ s^{-1}}\right) = 0.15g^{0.5}D_{50}^{1.5}S^{-1.12} \tag{10}$$

where D_{50} is median bed-material grain size (m).

Results from the Schoklitsch (1962) equation were compared with bed-material transport estimates obtained with the Lefort (1991) formula. This latter is interesting because it relies directly the solid discharge to the liquid discharge without requiring the calculation of hydraulic conditions, always difficult to estimate in the case of floods affecting streams with steep longitudinal gradient. This equation is defined as:

$$Q_sQ^{-1} = 4.45\left(D_{90}D_{30}^{-1}\right)^{0.2}\left[\rho_w(\rho_s - \rho_w)^{-1}\right]S^{1.5} \times \left[1 - \left(Q_cQ^{-1}\right)^{0.375}\right] \tag{11}$$

where Q_s is bed-material discharge ($\mathrm{m^3\ s^{-1}}$), D_{90} is particle diameter for which 90% are finer (m), D_{30} is particle diameter for which 30% are finer (m), and Q_c is critical water discharge ($\mathrm{m^3\ s^{-1}}$), defined by the equation:

$$Q_c\left[\sqrt{\left(gD_{50}^5\right)}\right]^{-1} = 0.295S^{-2.16}(1 - 1.2S)^{2.67} \tag{12}$$

4. The June 2000 flood, a classic event

4.1. A hydro-meteorological event

This large event was caused by the conjunction of both triggering and aggravating factors. First, from June 10 to 14, the catchments of the Upper Guil River and its left bank tributaries (Maloqueste, Ségure, Peynin, Aigue Agnelle) received some heavy rain (Abriès 276 mm, Saint-Véran 202 mm, Château-Queyras 140 mm) (Fig. 4), which amount was probably higher on the upper slopes than in these valley stations. Compared to the 1957 rainfall, that of June 2000 was not exceptional but, in contrast to 1957, it was strictly localised and concentrated over the upper ridges of the Upper Guil catchment and the Mt. Viso massif. Both the chronology of the event and the maximum hourly intensity (>17.3 mm $\mathrm{h^{-1}}$) of precipitation recorded explain the immediate

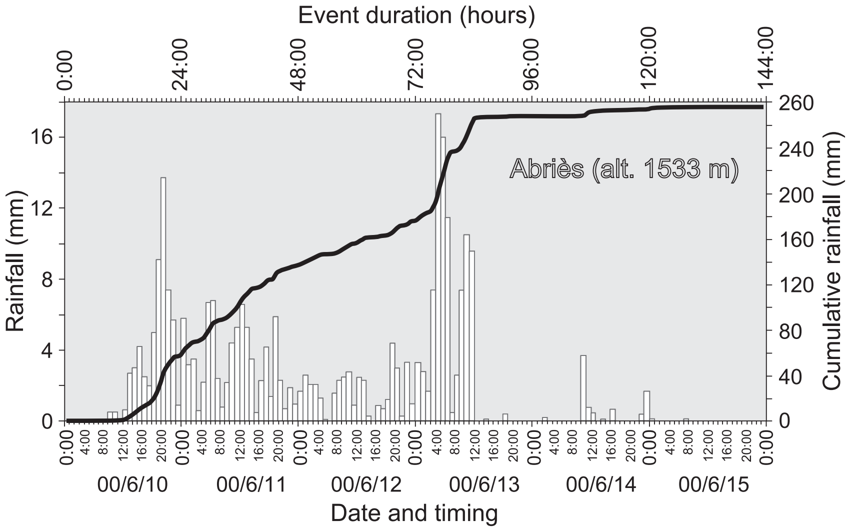


Fig. 4. The June 2000 meteorological event, Abriès station (1536 m), where the cumulative maximum rainfall was recorded in the valley. The event lasted 4 days, with two rainfall peaks; the second one occurred at the same time as the maximum flood wave coming from the Upper Guil River (source: MétéoFrance and EDF, 2000).

response of the hydrological system and its general destabilisation. The rainfall started from the southernmost part of the catchment (very Upper Guil subcatchment and its first-order tributaries such as the Maloqueste), then moved northwest, propagating downstream at the same pace as the flood wave (Beaudouin and Cossart, 2000). The Ségure was affected then the Bouchet, whose flows converged simultaneously with those coming down from the Upper Guil River. On the morning of the 13th, the Guil flood wave reached Aiguilles at about the same time as the Peynin overflowed its cone. The flood then moved down to Ville-Vieille and Château-Queyras, and eventually reached the Maison du Roy dam. The Aigue Agnelle/Aigue Blanche subcatchment was less affected, the rain being confined to the upper slopes.

Aggravating factors reinforced the effects of the flow event. On the upper slopes of the catchment, most of the winter snow had only recently melted, so that the soils were still saturated and so unable to absorb more water. Moreover, intense runoff along the mixed torrent/avalanche tracks of the steep, southeast facing mountain slopes was exacerbated by the fact that humid air mass was coming straight from the southeast, and thus directly affected these mountain slopes.

4.2. Hydro-geomorphic impacts on the Guil tributaries

The ultimate effect of this sequence of events was substantial runoff and sediment supply by the headwaters (Fort et al., 2002). Cut into slaty, schist bedrock, first-order catchments provided a great quantity of frost-shattered debris, mobilised as debris flows or hyperconcentrated torrential flows. The sediment was composed of a mixture of fine and coarse material, with maximal grain size exceeding 3.65 m^3 (Peyronelle torrent). Parts of this debris locally accumulated at breaks of slope (12,000 m^3 being deposited on the Peyronelle fan), regardless of whether or not there was a forest cover, while other parts were transported by the Guil tributaries (Peynin, Ségure), the channels of which were alternately eroded (destruction and incision of gravel bed armouring) and aggraded (accumulations of poorly sorted gravelly/bouldery bars) (Fort et al., 2002). Adjacent banks or slopes were locally subjected to failures and landslides: in the Ségure, >25,000 m^3 debris were supplied by the lower slopes to the riverbed (Debail, 2002), whereas in the very Upper Guil River, the same processes provided about 28,000 m^3 of sediment (Bourbon, 2002). We noted that nearly all active landslide sites were located on former landslide scars created during the 1957 flood. Along the Peynin, a third-order Guil tributary, the average sedimentary volume mobilised during the 2000 flood was estimated as >82,000 m^3, roughly equally supplied by landsliding and riverbank cutting (Einhorn, 2002).

The lower slopes all contributed significantly to the addition of mixed, fine and very coarse sediment

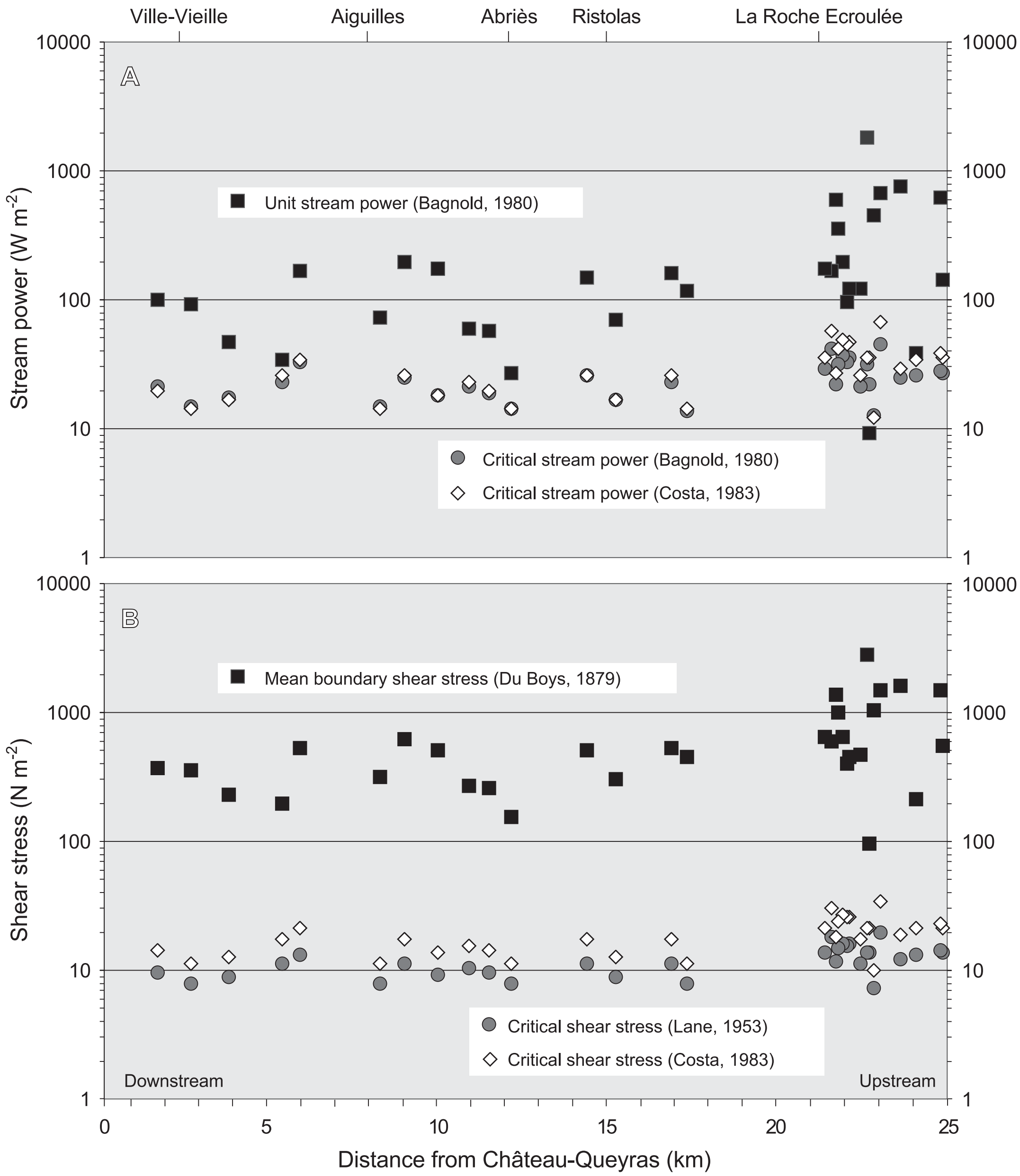


Fig. 5. Longitudinal distribution of stream power (A) and shear stress (B) in the Guil Valley, from its source down to Château-Queyras (June 2000). Important fluctuations in the hydraulic parameters are due to variations in longitudinal slopes. Note that values of critical stream power are everywhere lower than the values reached during the flood, a fact that explains the large volume of sediments mobilised and the high transport capacities.

load to the channel, thus giving a sediment yield of 2540–3925 m^3 km^2 (very Upper Guil River), 5310 m^3 km^2 (Ségure Torrent) and 7665–11,000 m^3 km^2 (Peynin Torrent). This substantial sediment yield resulted in rapid change in flow mode (i.e., debris flows, hyperconcentrated flows). Moreover, factors such as fluctuations in rainfall intensity, breaking up of log jams, or the presence of nonadjustable, rocky reaches along the longitudinal profiles, explain the discontinuity and the rapid shift in both space and time of the different hydro-geomorphic processes during such events.

In fact, the specific stream power of these streams was greater than their critical stream power, which explains the abundant solid discharge effectively transported during the flood (the discharge amount

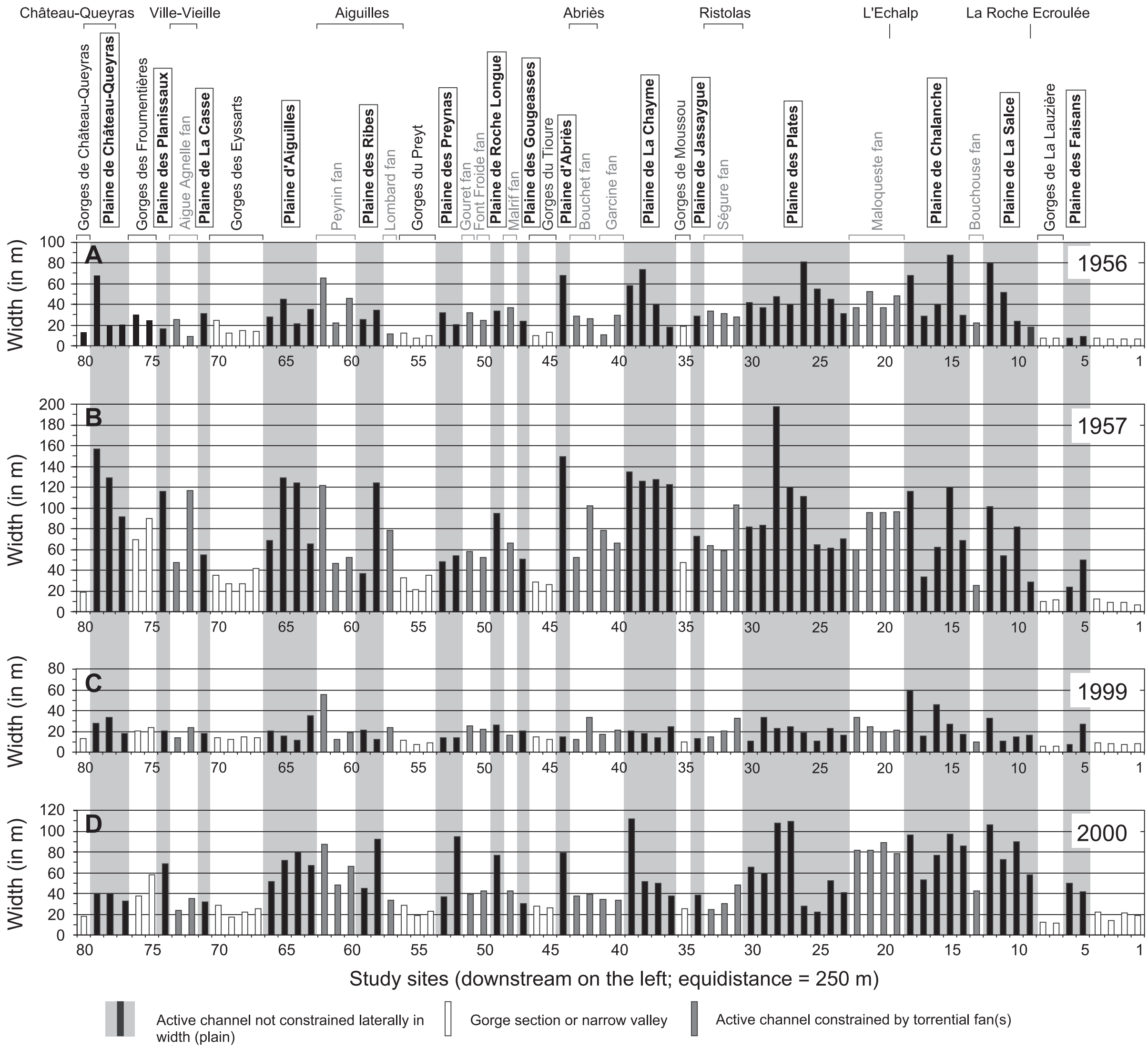


Fig. 6. Comparison of the active channel width of the Guil River before and after the June 1957 and June 2000 events (active channel width measured on IGN aerial photographs dated from 1956, 1957, 1999 and 2000). The amplitude of variations in active channel width depends on the section type (constrained or not by the presence of rocky outcrops and/or tributary fans). Upstream of La Roche Ecroulée (site 9), the impacts of both events are comparable, and the June 2000 event might even be larger. Downstream, the active channel width in 2000 was only about 40% of the 1957 channel width; yet locally (upstream of short gorge sections), the width was similar during both events.

Fig. 7. (A) In the Preyt gorges, upstream of Aiguilles, the Guil channel is narrowed by the concrete wall and road embankment (right bank). Adjustments to fluctuations of discharge can only be accommodated on the left bank (landslides affecting the weathered slaty bedrock). Additionally, the concrete wall deflects the flow onto the opposite (left) bank with minimum loss of energy, reinforcing the destabilisation of the bank. (B) Aerial view of the confluence between the Guil River and the Maloqueste Torrent after the 2000 flood. Sediment and water transported by the Maloqueste Torrent deflected the Guil River onto its right bank. In addition, the Guil River enlarged its active channel to the detriment of the flood plain (change of a single-thread channel to braided channels). Both processes produced combined effects, with destruction along the right bank [parking area washed away (P), a 300-m-long stretch of the D947 road eroded (*), re-opening, right in front of the Echalp houses, of a former channel closed by the road embankment (double dashed line)] (RTM photograph).

also being conditioned by the characteristics of the catchment debris supply). Along the Ségure tributary, specific stream power was estimated to range from 121 to 1350 W m^{-2}, whereas along the Peynin tributary, estimates ranged from 227 to 1404 W m^{-2}, and along the debris-flow prone Peyronelle subtributary, it was estimated to be 5489 W m^{-2}. In contrast, estimates for the uppermost reaches of the Upper Guil River were lower (63 to 1128 W m^{-2}: Fort et al., 2002). All these values are minimum estimates.

4.3. Hydro-geomorphic impacts on the Guil Valley

The maximum discharge of the Guil River was estimated (Koulinski and Lefort, 2000) to be 180 m^3 s^{-1} at Aiguilles (1957: 315 m^3 s^{-1}), for an mean annual discharge of 6 m^3 s^{-1} and a mean June discharge of 18 m^3 s^{-1} (SOGREAH et al., 1991). From the Roche Ecroulée to Château-Queyras, the specific stream power, always higher than the critical stream power, was estimated to vary from 51 to 276 W m^{-2} (Fig. 5). This explains the high transport capacity, estimated to be 105–140 m^3 km^{-2}.

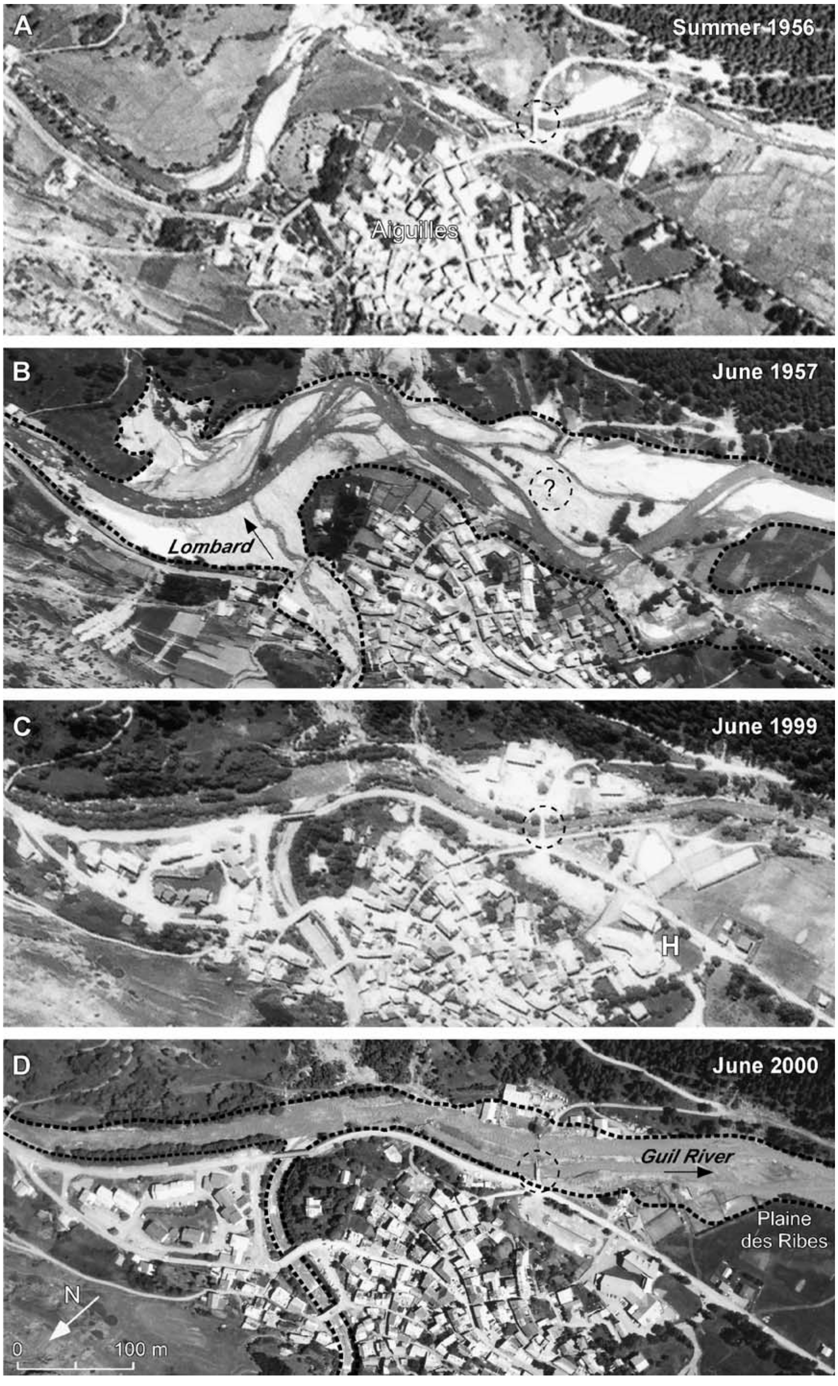
The flood impacts on the Guil valley floor were influenced by variations in the floodplain and/or channel geometry, in particular by the succession of long, 250-m-wide stretches alternating with short, narrow gorge sections (Le Preyt, Château-Queyras), causing water impoundment upstream. The swelling of the Guil River caused the submersion of, and aggradation within, a large part of the floodplain (i.e., Echalp, Gouret, Aiguilles), generalised bank erosion (whatever the substratum, be it alluvial, colluvial, or schists) and quite systematic changes in the river pattern. The stream partially reoccupied some of its former channels, either abandoned or modified in their geometry by various structures (embankments, water intakes, bridges, roads, camping grounds, handicraft zones, ski tracks) built during the last four decades.

One major impact of the flood was the enlargement of the active channel and the generalised bank erosion observed regardless of the section considered (Arnaud-Fassetta and Fort, 2004) (Fig. 6). In the wider areas, river banks collapsed and retreated, thus reinjecting a large volume of sediment into the active channel. Very locally, the “1957 flood terraces” (Tricart, 1974) were eroded as well. In the narrower sections, bank undercutting triggered many landslides, to the detriment of colluvial, morainic or weathered bedrock slopes (Fig. 7A). Artificial channel segments were also affected, with deterioration or partial destruction of dikes, gabions, concrete or blocky-armoured walls. For instance, the gabions and earthy dike protecting the camping ground of Le Chardonnet (Ristolas) were seriously undermined, and directly threatened the safety of campers (Koulinski, 2001). Also, most of the wooden footbridges used for hiking or cross-country skiing were washed away.

On the floodplain, flooding and aggradation were common, notably upstream of the gorge sections. Upstream of Ristolas, a new channel opened between the road embankment and the houses of Echalp hamlet (Fig. 7B). The water pool at La Garcine (upstream of Abriès), encroaching upon the flood plain, was drained while the area recovered its function as an active river bed. Upstream of the Preyt gorges and Aiguilles, the large camping ground of Le Gouret was flooded under

Fig. 8. Sequential series of aerial photographs displaying channel change of the Guil River at Aiguilles. (A) During summer 1956. The Guil River is wandering with alternate bars, flowing in a rather large active channel resulting from the 1953 flood. The riparian vegetation is very sparse. There are two bridges, the Peynin bridge and another downstream. (B) June 1957. The wandering pattern has been accentuated, together with a dramatic enlargement of the active channel width. Upstream, the sediment load carried by the Lombard Torrent extended across the Guil channel; the riparian forest was destroyed and/or buried; the Guil River was deflected onto its opposite (left) bank, thus triggering landslides; downstream, both bridges were washed away, and the road was destroyed along a 0.6-km-long stretch. (C) June 1999. The Guil River course is the result of the flood control scheme implemented after the 1957 flood. Both the Guil and the Lombard rivers have been channelised, with concrete bed armouring built at their confluence. The channel course of the Guil River has been straightened, thus favouring acceleration of flow. No serious flood has affected the Guil River since 1957. The Peynin bridge has been rebuilt in the same place, and the village has been enlarged along both banks [habitations, handicraft zone, hospital (H), sports ground], upstream of the Lombard confluence and downstream in the “Plaine des Ribes”, in places that had been severely affected by the 1957 flood. The riparian forest has developed as well (even on river islands). (D) June 2000. The photo was taken just at the end of the flood. The Guil River by-passed the Peynin bridge, partly re-occupying its former course by enlarging its active channel whose width is quite reduced compared to that of 1957. The riparian forest has been partly destroyed upstream of the Lombard confluence. The Lombard subcatchment was not affected by the flood (IGN and RTM aerial photographs).

about 2 m of water. The resulting decrease in velocity caused the abandonment of the transported sandy load with, in some places, 1.5-m-thick deposits displaying ripple marks suggesting tractive water flows. Obviously, the river reoccupied part of its floodplain as an efficient way to dissipate its excess energy.



At a more general level, numerous changes affected the river pattern, as becomes evident when comparing the 1999 situation with that prevailing after June 2000. In 1999, the Guil River had a single-thread channel, bordered by vegetated, gravelly and sandy banks, artificially channelised in places. After the flood, many stretches were (and still are in 2002) braided (Arnaud-Fassetta and Fort, 2004), as a response to the sediment supply into the riverbed (sections between Echalp hamlet and Ristolas, between Ristolas and Abriès). Other changes occurred at the confluences between the Guil River and its tributaries. For instance, the Maloqueste subcatchment (left bank) delivered a voluminous debris flow that spread across its confluence fan, the water and debris encroaching upon the Guil floodplain, then deflecting the Guil onto its right bank, thus causing the destruction of a 300-m-long stretch of the road at the Echalp hamlet (Fig. 7B).

Other indirect impacts occurred subsequent to the flood. In fact, the context prevailing before the flood was predominantly narrowing and incision, as observed along the upper Guil River prior to the June 2000 flood (e.g., comparison of long profile and/or cross sections surveys, undermined structures such as bridge piles, etc.; Parc Naturel Régional du Queyras, 2002). This trend, generally interpreted as an adjustment to land-use change (afforestation) and torrential control works, is in agreement with the behaviour of other alpine streams (Bravard et al., 1997; Liébault and Piégay, 2002). This trend was

Fig. 9. The Peynin bridge at Aiguilles, during and after the 2000 June flood. (A) June 13th. Oblique aerial view (RTM) showing the Peynin bridge nearly buried by sediment and the new channel opened by the Guil River on its left bank. The cross-sectional area was 82 m^2. (B) June 14. Detail of the Peynin bridge, blocked by sediment (PNRQ). The cross-sectional area is reduced to 8.68 m^2. (C) July 2000. The Guil channel has been dug out, and the gravels removed have been piled on both banks as levees to re-establish one single channel flowing under the Peynin bridge. (D) May 2002. The upstream-progressing erosion subsequent to the dredging of the Guil riverbed has undermined the base of the bridge piles. Concrete stone armouring has been built in order to protect the right bank and the hospital downstream, whereas the left bank has been left unmanaged.

temporarily offset by the flood (abundant aggradation), but was reset with the lowering of the flow, thus causing more destabilisation (undermining) of the existing protective structures such as river dikes or road embankments. This also made the entire torrential system more sensitive to subsequent "minor" events (i.e., avalanches of late winter and spring 2001, 10- to 15-year R.I. floods of October 2000 and July 2002).

4.4. Case study: Aiguilles

The worst damage took place at Aiguilles village where the Guil waters, flowing rapidly through the "Preyt gorges", spread over the "Plaine des Ribes", opened new channels on one side of the bridge and destroyed many commercial buildings. One kilometre downstream, the Guil waters were impeded again at the Peynin confluence, where this uncontrolled tributary

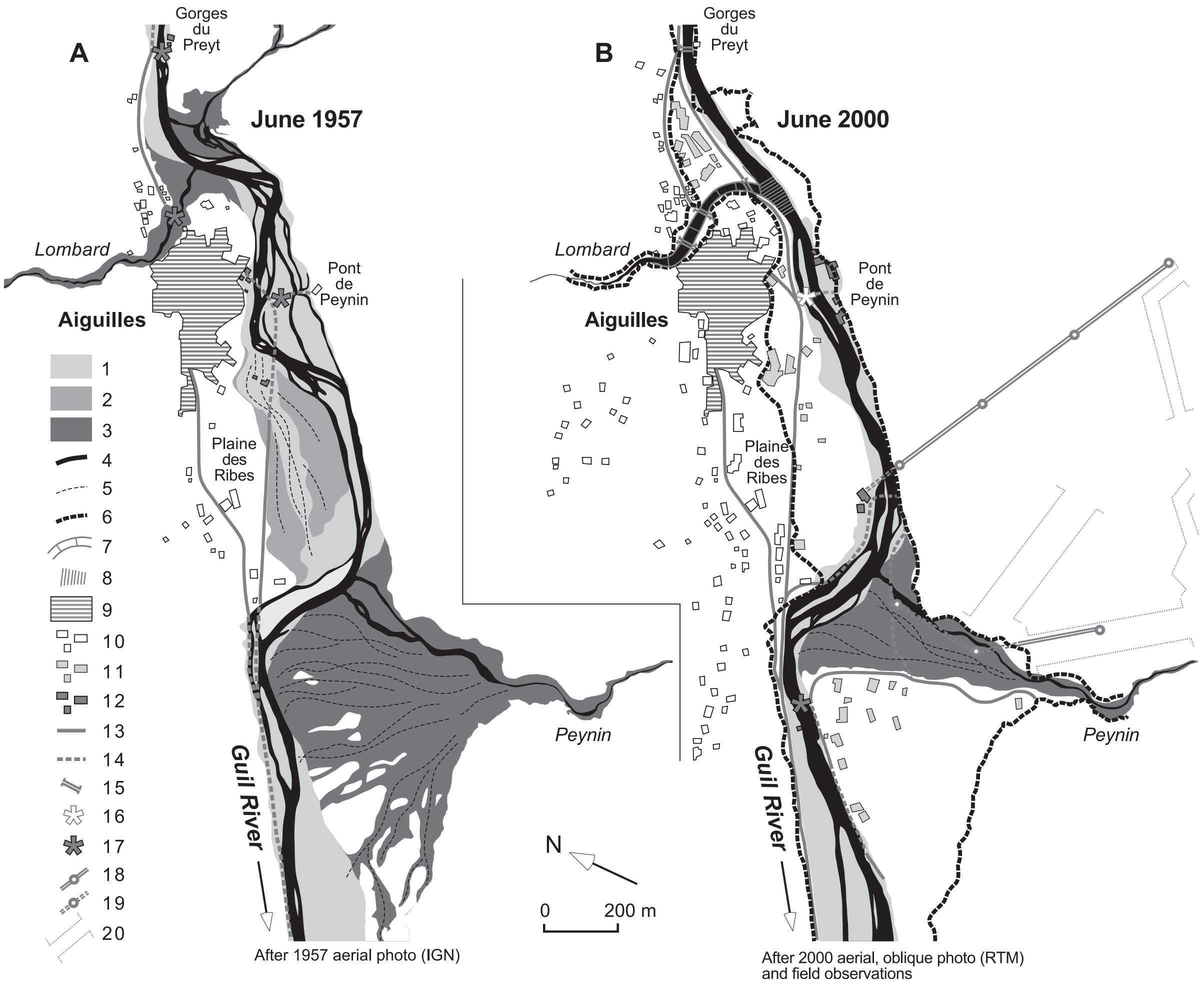


Fig. 10. Comparative maps showing flood impacts and land-use changes that took place in the Plaine des Ribes (Aiguilles village) between 1957 and 2000. Obviously, the vulnerability of this village has increased, due to the many buildings and activities sited in the former 1957 active channel of the Guil River and on the Peynin fan. 1=1957 active channel; 2=floodplain; 3=zone of aggradation (torrential fan); 4=main channel; 5=secondary channels; 6=1957 flood plain extent; 7=flood control structure: concrete embankment and weirs; 8=channel degradation control structure: concrete bed armouring; 9=village; 10=building away from the 1957 flood plain; 11=building sited on the 1957 flood plain, not flooded in 2000; 12=damaged building; 13=road; 14=damaged or destroyed road; 15=bridge; 16=aggraded bridge; 17=damaged or destroyed bridge; 18=ski pylon; 19=damaged or destroyed ski pylon; 20=ski run.

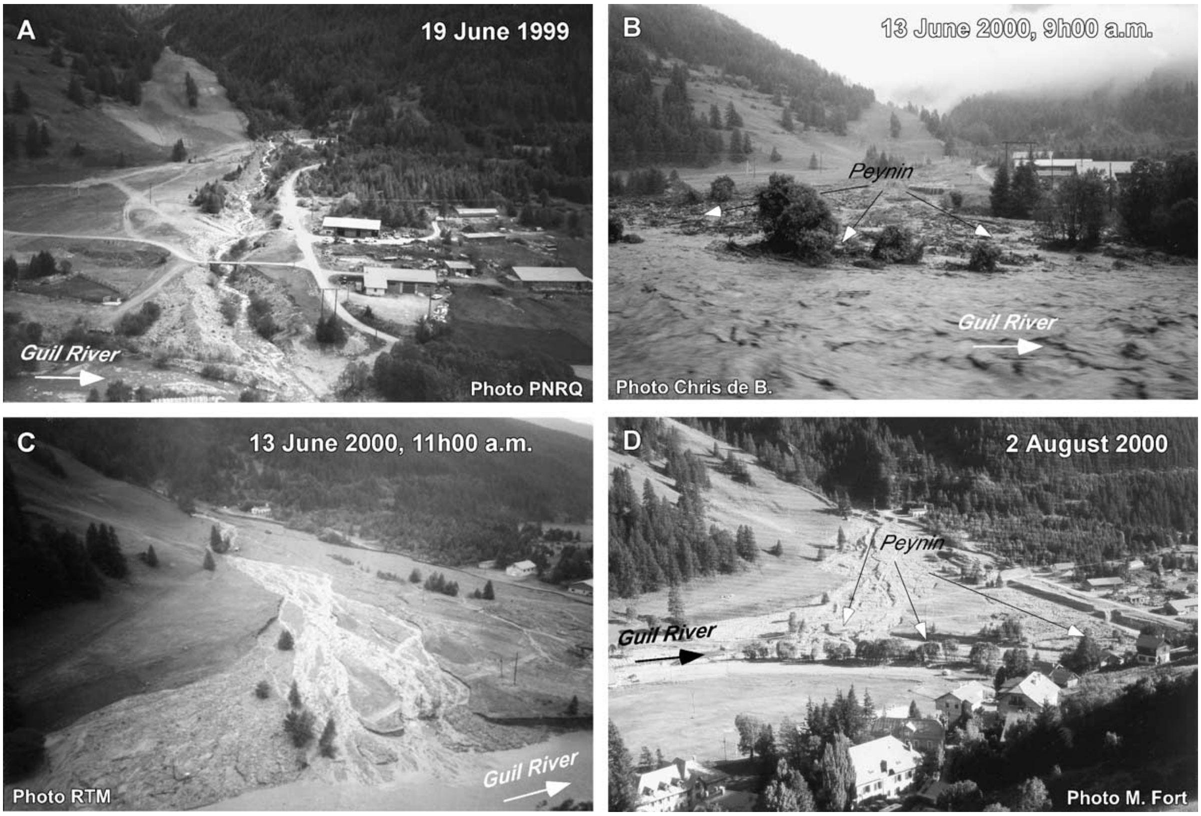


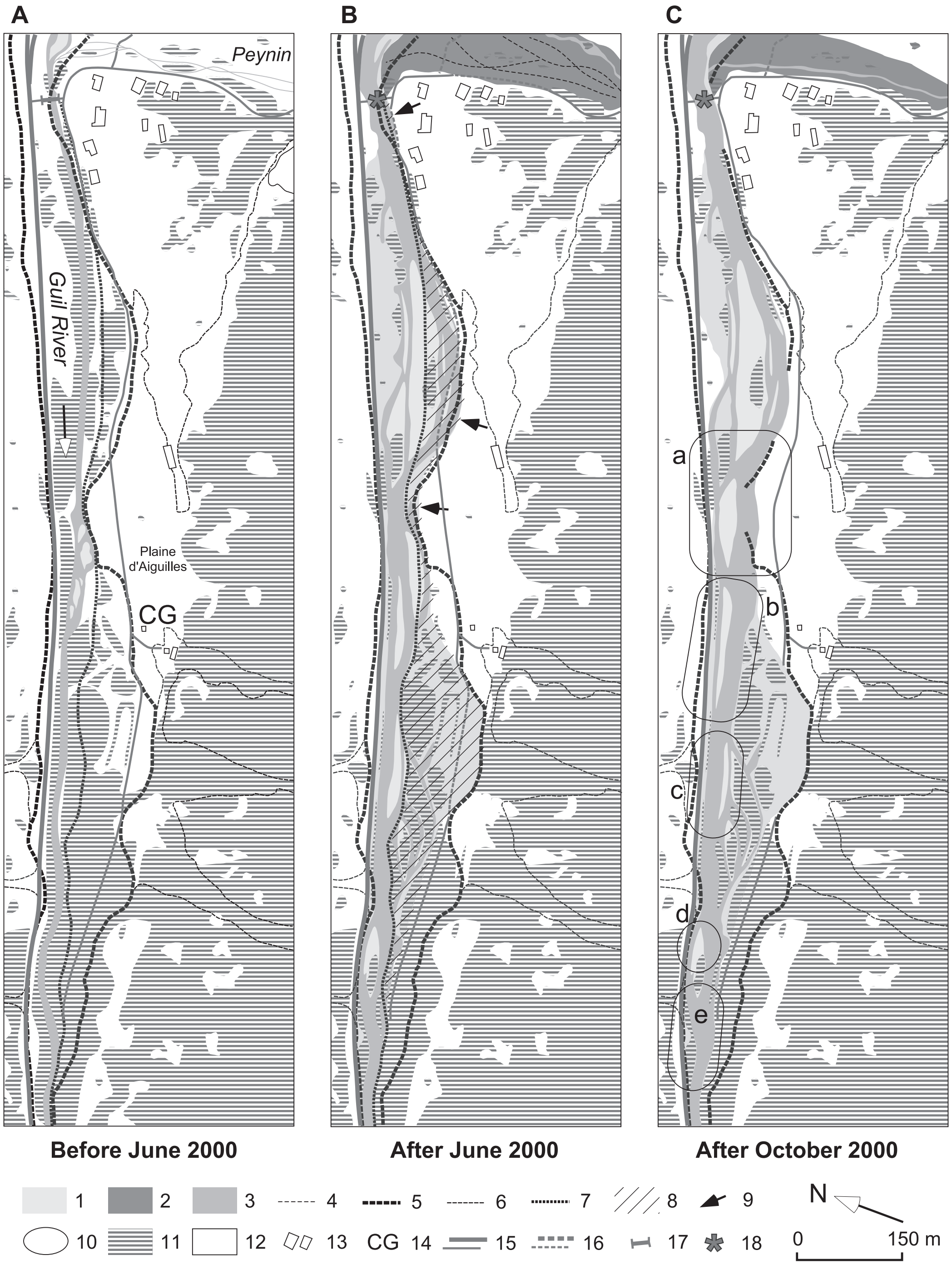
Fig. 11. Sequential series of photographs showing changes that occurred on the Peynin fan before (A), during (B), a few hours after (C) and a few weeks after (D) the overflowing of the Peynin fan. Before the 2000 flood, the fan was partly occupied by a handicraft zone (left bank) and by ski runs and installations (right bank). On the morning of June 13, the right bank was breached. The transport capacity of the Peynin, reinforced by its traverse through steep gorges upstream, explains the amount of debris suddenly deposited on the fan. A few weeks later, a new straight channel had been artificially dug out, and the right bank has since been re-shaped by bulldozing to restore the ski runs.

overflowed its right bank and injected more water and debris into the Guil River.

Several processes came together to produce catastrophic consequences. In the Preyt gorges, the water level and the power of the Guil River increased, thus favouring landsliding on the left bank and the blocking then the destruction of both a small dam and a water intake on the right bank. The high discharge of the Guil entering the Aiguilles basin caused partial destruction of the riparian forest (Fig. 8C) and overbank flooding (82 m^2 cross-sectional area) near Peynin bridge, in particular because of gravel aggradation in the channel and the subsequent reduction in the cross-sectional area under the bridge (from 31.58 to 8.68 m^2) (Fig. 9). The waters, prevented from flowing on the right bank by the road embankment and by additional protection (sandbags) for the hospital (Fig. 8D),

Fig. 12. The Peynin fan before and during the June 2000 flood, the Guil River naturally expanded across the Plaine d'Aiguilles, dissipating its energy by widening its active channel over the 10-year flood limit, by lateral cutting and eventually by braiding. New channels were opened across forested areas established on the "1957 flood terrace". The destabilisation of the fluvial system can be appreciated from the effects of another minor flood that occurred in early October 2000. 1=active channel; 2=zone of aggradation; 3=main channel; 4=secondary channel; 5=100-year R.I. flood limit on the Guil River; 6=100-year R.I. flood limit of the Guil tributaries; 7=10-year R.I. flood limit on the Guil River; 8=June 2000 morphodynamically active area beyond 10-year R.I. flood limit; 9=June 2000 morphodynamically active area beyond 100-year R.I. flood limit; 10=major morphodynamic adjustments between June and October 2000; 11=forest; 12=field or stripped soil; 13=building; 14=camping ground; 15=road; 16=damaged or destroyed road; 17=bridge; 18=destroyed bridge.

spread over the left bank, in the handicraft zone, thus reoccupying their former (pre-1957) channel course (Fig. 10). The two buildings of the carpenter's workshop, one civil engineering company building, and a small house were damaged. Overbank flow also occurred on the right bank downstream of the



bridge, destroying the swimming pool and threatening a restaurant. Further down the Plaine des Ribes, light, wooden bridges (used for cross-country skiing) were swept away.

At the Peynin confluence, the Plaine des Ribes was inundated, and the Guil River was deflected against its left bank, blocked by the road embankment, which suffered some damage. The excess sediment load carried by the Peynin Torrent (debris-flow pulses), in addition to the sharp slope break at the confluence with the Guil Valley, caused instantaneous aggradation (Fig. 11). The resulting blocking by debris of the straight, artificial channel, together with the formation of log jams concentrated around a narrow bridge downstream, forced the Peynin Torrent to change its course and to overflow its right bank (resulting in destruction of ski installations, in particular of a water intake for artificial snow). In fact, the Peynin Torrent swept across its fan, and accumulated a volume of debris estimated to be 15,000 m^3 (Beaudouin, 2001).

Further downstream, the Guil was deflected by the road embankment, causing it to swing against its opposite (left) bank, which was then eroded well above the decadal flood limit. A section of the dirt road and pieces of land underlain by the "1957 flood terrace" were washed away (Fig. 12).

5. Discussion on the role of human impact on flood effects

Two types of structures require consideration, namely those related to flood prevention and those arising from recent changes in the local economy.

5.1. To what extent were the post-1957 flood control structures aggravating factors?

First, comparative study of the geomorphic consequences of both the 1957 and 2000 floods provides a basis for assessment of the efficiency of flood control structures built after the 1957 event. On the one hand, the flood was partly controlled by the post-1957 preventive structures (Ségure, Lombard, Aigue Agnelle). At the Ségure/Guil confluence, for instance, the Ségure flows have been constrained and their velocity accelerated by embankments, in order to protect Ristolas village and to avoid repetition of the disastrous 1957 flood, during which the Ségure swept over the entire village, causing aggradation that locally exceeded 6 m in thickness (Fig. 13). In 2000, the artificial channel efficiently constrained the flood. In contrast, the absence of post-1957 protection on the Peynin fan (an omission arising from the fact that the fan at that time was devoid of any human use) caught out Aiguilles villagers in 2000; it appears to have been forgotten that, in 1957, about 30,000 m^3 of debris (SOGREAH et al., 1991) had spread over the Peynin fan. We thus think the contrasting responses of the Ségure and Peynin torrents are directly related to the mitigating effect of engineering works conducted or not on their alluvial fans. This assessment is supported by the fact that other factors, such as geology, relief, sediment sources, land-use, are very similar in both catchments and do not create different landscape sensitivity to rainfall. Another factor that might explain a contrasting response would be that rainfall was not uniformly distributed in space; this assumption cannot be entirely ruled out, however both reports by local people and observed geomorphic effects in these upper catchments suggest the rainfall intensities and duration were not significantly different.

Clearly, therefore, the flood-mitigation structures installed have a certain effectiveness. On the other hand, some of them (such as those around Ville-Vieille) were partly damaged in 2000 due to poor maintenance (Fig. 14). Thus, their effectiveness in the face of a flood greater than a 30-year recurrence period may be seriously questioned.

Second, some man-made structures such as under-designed bridges, or the upstream/downstream discontinuities and irregularities in the degree of channel management, were obviously aggravating factors. At Aiguilles, the Peynin bridge is quite narrow, and its cross-sectional area is too small to accommodate flood discharges greater than the 10-year R.I. flood, especially if important aggradation takes place as occurred during the 30-year R.I. 2000 flood (Fig. 9B). In Ristolas, the presence of a concrete weir built at the downstream bridge has artificially maintained the longitudinal profile of the Guil River at a level higher than would have occurred in natural conditions. The weir was destroyed during the June 2000 flood, thus

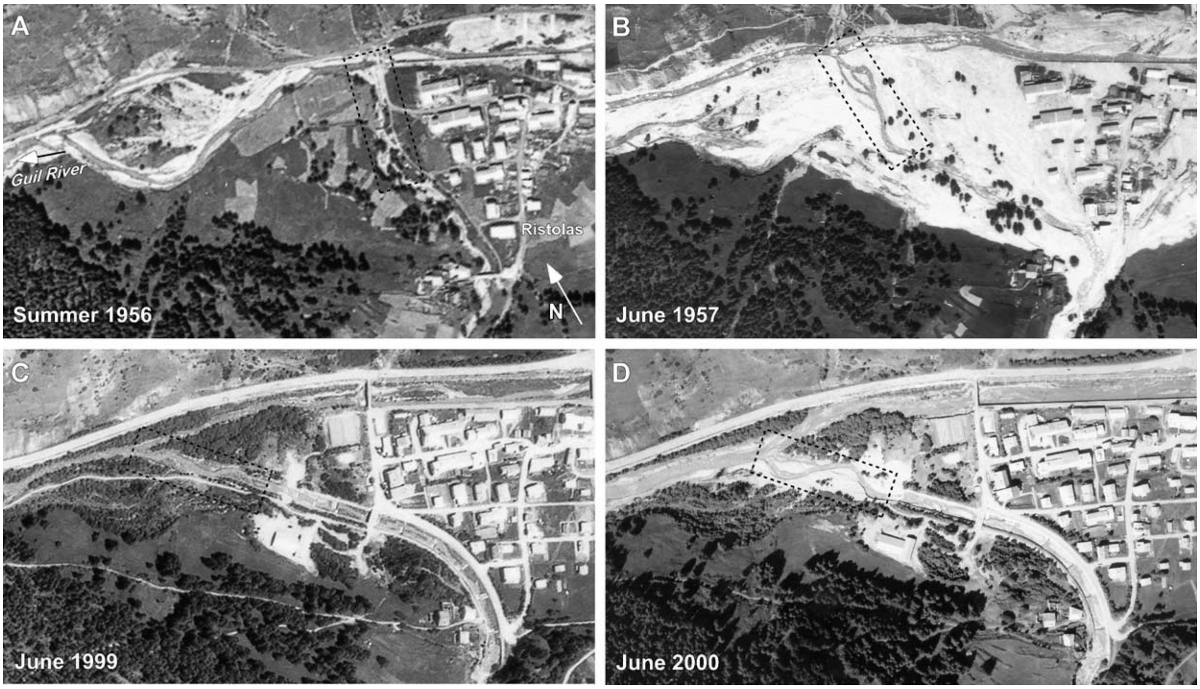


Fig. 13. Sequential series of photographs showing changes that occurred at Ristolas and on the Ségure fan, at the confluence with the Guil River. (A) Ristolas village is sited on the right bank of the fan. During summer 1956, the Ségure channel was narrow, partly colonised by riparian vegetation. (B) The 1957 flood extended across the entire fan. The village streets were covered with sediment to a depth locally exceeding 6 m. Agricultural land was devastated. (C) Flood control structures were built after 1957, so that the Ségure joined the Guil River at a very acute angle. In 1999, the Ségure was well constrained by the artificial channel (concrete-stony walls) along which weirs can be seen. (D) June 2000: after the flood, the only changes consist of an accentuation of the meandering channel trace and incipient braiding of the Ségure close to its confluence with the Guil. The post-1957 anthropogenic channel has efficiently protected the village, though a few weirs have been damaged.

threatening the stability of the bridge, which collapsed a few weeks later, during another, 10-year R.I. flood (October 2000).

5.2. Land-use extent and its impact on flood dynamics

Comparison of the 1957 and 2000 situations also demonstrates the role played by land-use changes in aggravating the flood impact. With the abandonment of the traditional agro-pastoral life in favour of a winter ski-based and summer mountain-hiking economy, more buildings and infrastructure were constructed on the flood plain and are now in danger of being flooded.

Camping grounds are generally located on the floodplain, quite often on the vegetated “1957 flood terraces” and along former, now inactive channels; yet the threat is still present. As already pointed out, the camping ground of Le Gouret was submerged during June 2000. Occupied by fields before 1957, this left bank floodplain was severely affected (eroded and submerged) during the 1957 flood, so that the landowner decided to sell his land to the village council, which then converted it into a large, pine-planted camping ground. At Ristolas, the June 2000 flood level rose to a level only 30 cm below the dikes and gabions that border the camping ground of Le Chardonnet. Similarly, the Château-Queyras camping ground (right bank) seems to be protected by the D947 road embankment; however, it lies in the middle of the 1957 flooded area (Fig. 2D). More generally in the villages (Abriès, Aiguilles, Ville-Vieille), the only space available for the development of economic activities (shops, handicraft zones, sports grounds, ski runs) is the wide, flat floodplain on either bank of the river. The local population had approved all these developments because, during the last four decades, no major flood had occurred, the river having naturally

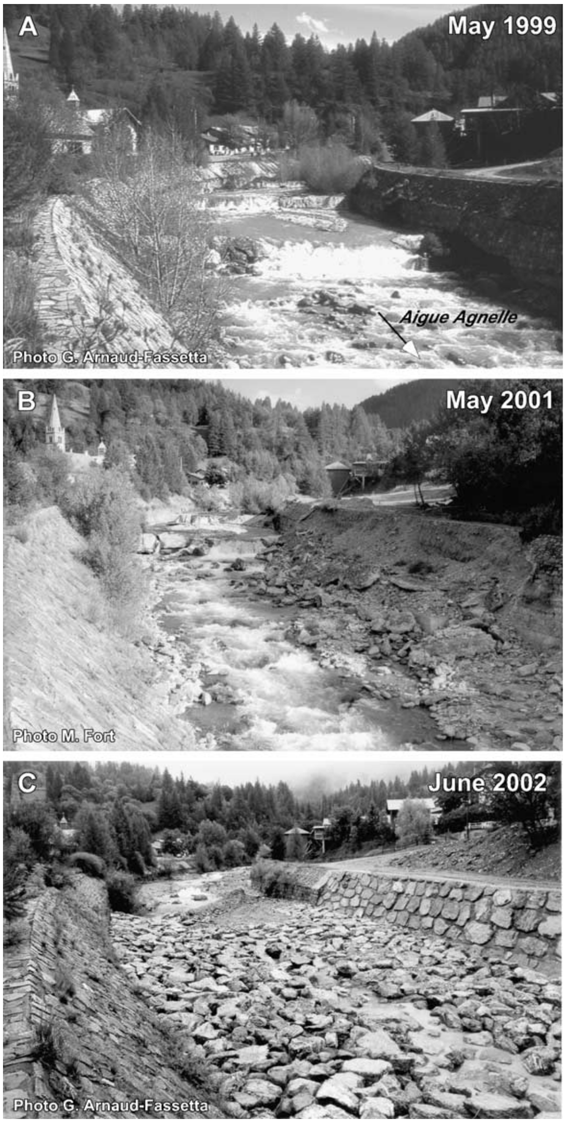


Fig. 14. (A) Hydraulic works (weirs, concrete bank armouring) along the Aigue Agnelle course on the Ville-Vieille fan. (B) Note the important damage to structures following the 2000 flood, due to channel degradation and widening on the convex (left) bank. (C) During summer 2002, the channel floor was repaired and a bed armouring consisting of concrete blocks was built.

contracted into its active channel, and so obliterating the evidence of its potential catastrophic behaviour. This land-use change has obviously increased the vulnerability of the valley and its population.

Some other structures have directly reduced channel capacity. In wide sections, such as upstream of Ristolas for instance, parking grounds (Roche Ecroulée, Echalp) have been built directly in the floodplain. Initially destroyed in June 2000, they have been destroyed on two occasions since (October 2000 and July 2002) by 10-year return period floods only. However, as they are considered to be a good investment for summer tourism, they are repeatedly rebuilt at low cost (bulldozer flattening of gravels). The same holds true for cross-country ski runs, generally underlain by gravels piled up against road embankments along the river; they are usually the first to be eroded, and so may be considered as a low-cost road protection against floods.

Reduced channel capacity arising from anthropogenic structures may also affect gorge sections. In 2000, the water intake (for Aiguilles hospital) and the dam built in the Aiguilles (Preyt) gorge had the effect of narrowing the channel even more, and thus increased artificially the rise in water levels upstream, aggravating the submersion of the camping ground of Le Gouret. In the same narrow gorge, the retaining concrete wall of the D947 road caused deflection of the flow on to the opposite (left) bank, thus exacerbating landsliding and supplying the Guil River with abundant gravelly and finer sediments (Fig. 7A). The resulting increase in flow rate gave rise to supersaturated pulses, causing rapid destruction of the riparian forest and excessive dumping of bed-material load where the Guil River entered the Plaine des Ribes in Aiguilles (Figs. 8D and 9A,B).

5.3. Were the post-2000 flood river management scheme really efficient?

In answering this question, the conditions under which the management measures were undertaken must be recalled. (1) There was an emergency situation, because the entire Upper Queyras was isolated (road segments destroyed, bridges undermined) from the lower part of the Guil River and from Guillestre in particular; the only road open was that crossing the 2360-m-high Isoard Pass. (2) The flood occurred only a few months before local elections, so that it is realistic to assume that candidates again seeking re-election may have sought to demonstrate their efficiency in improving such a dramatic situation. Therefore, most measures were taken immediately, without real consideration of what should have been an integrated river basin management scheme. Most actions taken were of relatively low cost and meant to be only temporary. These measures consisted of narrowing and dredging the channel cross section, correcting the channel course and re-establishing as rapidly as possible the conditions for economic activity (road foundations and embankments, road- and foot-bridges, parking areas, etc.).

One generalised action (along both natural and urbanised reaches) was the narrowing of channel cross-sectional area by artificial levees, built with loose gravels taken up directly from the river channel (Fig. 9C). These stone dikes, stretching parallel to the low water channel, were meant to restrict the braiding river course within one channel as had been the case before the flood, and to force the river to incise its alluvial floor, thus indirectly reducing the frequency of overbank floods. However, we speculate that this approach is illusory. First, bed armouring prevents channel incision during annual floods, so that the channel capacity remains insufficient for a 10- to 30-year flood event. Strong riverbed degradation (armour removal) increases the critical height of the levees for planar/slab failure. Second, during extreme events, these artificial levees offer little resistance to erosion because the channel competence during flood is greater than the resistance offered by the grain-size of the material constituting the artificial levees. In these conditions, the channel tends to widen and to be infilled, causing a higher flood risk in the flood plain (Fig. 15A).

A complementary measure adopted was the excavation of the Guil channel, designed to increase the cross-sectional area and thus to avoid another catastrophic, overbank flood situation. In doing so, however, the managers introduced the possibility of upstream-progressing erosion, which may destabilise existing structures, including those dating from the older (post-1957) flood control schemes (Fig. 15B). This holds particularly true at Aiguilles, where both the dredging of the gravels, accumulated under the Peynin bridge during the flood (Fig. 9B,C), and additional artificially dredged 1.5-m-deep channel in the Guil River have induced regressive linear incision, threatening directly the piles of the Peynin bridge. Two years on from the 2000 event (summer 2002), regressive incision has reached, and has begun to attack, the concrete bed armouring built after the 1957 flood at the Lombard confluence (some 500 m upstream of the bridge). As a consequence, this important and formerly very efficient structure has been undermined and is rapidly deteriorating (release of stones, collapsing slabs), with a >3-m-deep plunge pool accelerating the process. Ultimately, this process constitutes a threat to the Lombard artificial channel that protects the eastern part of Aiguilles village (Fig. 10B). A similar, though less critical situation is also observed at Ristolas.

Another management intervention taken at Aiguilles only a few weeks after the flood was the digging of a new, straight, artificial channel for the Peynin stream, aligned at right-angles to the Guil River (Fig. 11D). Indeed, the handicraft buildings on the left bank had to be protected to the detriment of the right bank (ski runs). However, any further major flood is likely to see the re-establishment of the Peynin's course, which will continue to deflect the flow of the Guil onto the opposite (right) bank, thus posing a further threat to the already-damaged road embankment. In fact, a new scheme is under study, designed to deviate the entire Peynin course onto its left bank, in such a way that its confluence would join the Guil channel at a more acute angle (similar to the Ségure confluence), in order to avoid the damming effects of such tributary convergence (Koulinski, 2000). However, the decision has not yet been made to modify the Peynin course because of local interests and conflicts.

Other measures adopted have included rebuilding bridges, at the same places and sometimes of the same size as before the flood. Although, following its destruction, the bridge connecting the road to the Peynin cone, downstream of Aiguilles, was rebuilt with a wider roadbed (30 m instead of 16 m), and so able to absorb the effects of higher river discharges, the same rather small cross-sectional area was retained in the case of the intact Peynin bridge. In fact, because of the cost of such a structure, it was decided to wait until another major flood destroys the bridge, so that a new, larger bridge will then be constructed, and the left bank protected (handicraft zone). So far, the left bank has been left unmanaged as the lesser evil, for the flooding of the handicraft zone is considered less of a disaster than the flooding of the hospital (concrete rock-armouring rebuilt on the right bank; Fig. 9D).

This last example provides some insight into acceptable future valley management. In such high mountainous environments, it is preferable to keep most of the valley bottom clear of buildings, thus ensuring that the river has sufficient space to migrate

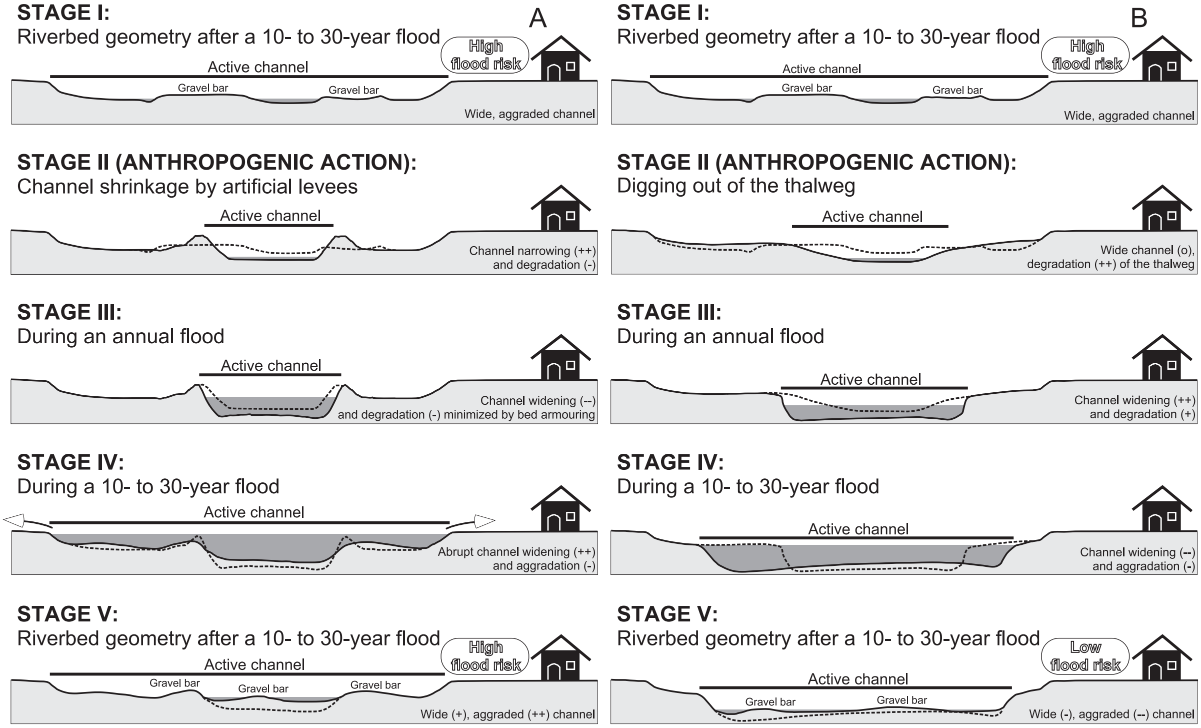


Fig. 15. Types of control measures on the active channel, involving (A) artificial levees and (B) excavation of the channel, with distinctive, speculative effects on evolution of the channel geometry. Note that cross-sectional area is the same in both case.

freely, dissipate its energy and so adjust to the extreme hydro-geomorphic conditions that characterise these low-frequency, high-magnitude floods. The various heavy structures (bridges, embankments, dikes, protection walls...), mostly restricted to areas of capital investment (villages, roads, buildings of particular economical interest), should be adjusted to the river dynamics. Other light structures (wooden footbridges, cross-country ski runs) should be adapted so that they are neither too difficult nor too costly to repair.

6. Conclusions

The Guil catchment is naturally prone to large, though rare floods. Accordingly, river management must take this hazard into consideration, in a context of sustainable development of the Guil Valley.

We have shown that a 30-year R.I. flood may be very geomorphologically active, from the very first-order catchment basins down to the main Guil River valley. Various slope processes act simultaneously (landslides, debris flows), supplying a large amount of water and debris that is alternately transported and deposited along the talwegs. The Guil riverbed underwent significant alteration. In fact, the entire active channel was destabilised, and has become sensitive to minor events.

During the 2000 event, the control structures built after the 1957 flood have proved to be rather efficient; yet they suffered some damage, suggesting that their maintenance must be improved. Temporary control structures built after the June 2000 flood are at the very least inefficient or, at worst, potentially dangerous. More generally, the comparison between the 30-year R.I. 2000 flood and the >100-year R.I. 1957 flood showed that, despite their different magnitudes, their hydro-geomorphic impacts seem, at least along the Guil River, always to occur in the same places. It is therefore possible to anticipate the hydro-geomorphic impacts of future floods by, for instance, reinforcing the major structures located in the most morphodynamically active zones.

Two different conceptions of river management are encountered locally. On the one hand, most villagers press for a rapid rehabilitation of the flood control structures, similar both in design and location to the existing (pre-2000) structures. They even make a case for better protection in order to include new settlements and activities developed in relation to the tourism economy. These projects require considerable amounts of money, in a context of restricted funding by the State agencies (Restauration des Terrains en Montagne, Direction Départementale de l'Equipement, Region). On the other hand, a large minority of people, most often supported by non-residents, are increasingly concerned about the quality of life and the environment, and see the river (together with the mountain environment) as a rich ecological system that has to be protected. They reject environmentally destructive structures (such as dredging or continuous embankment) and plead for more conservative, «light» structures (involving more local river training works than sophisticated civil engineering work), good enough to absorb the most frequent (10-year magnitude) floods; although undoubtedly damaged by the larger events, such structures can also be repaired at a lower cost for the community.

Like in any other part of the Western Alps, river management in Queyras should moderate the need for economic development with reference to hydro-geomorphic dynamics. Whatever the final outcome, any management scheme should allow the river sufficient space to dissipate its energy during flood events, as well as taking care to avoid siting buildings or other structures in dangerous places. This requires coordination at the river basin scale, between the different villages of the valley as well as between the various users of the stream waters, and cannot be implemented without prevention/warning systems adapted to a population living only seasonally in such a potentially hazardous environment.

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