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LANDFORM EVOLUTION IN MOUNTAIN AREAS

FREDERIC LIEBAULT (LYON)

MORPHOLOGICAL RESPONSE OF AN ALPINE TORRENT TO WATERSHED REFORESTATION (THE SURE TORRENT, SOUTHERN FRENCH PREALPS)

Abstract. This paper reports a study of the morphological response of a steep, upland, gravel-bed river to substantial watershed reforestation caused by 1) implementation of an erosion-control scheme and 2) rural depopulation following World War Two. Historical documents and dendrochronological dating of recent terraces show that accelerated narrowing of the active channel occurred after 1950. This channel adjustment was the result of an upstream-driven terrace formation process induced by a sediment supply decrease in headwater sub-basins. The degradation process propagated downstream at a mean rate of 500 m · yr^{-1}. Consideration of the nature and timing of the channel response indicates that spontaneous reforestation induced by rural abandonment had the greater geomorphic effect.

Key words: Southern Prealps, channel response, historical analysis, dendrochronology, reforestation

INTRODUCTION

In the French Alps there are approximately 2,000 torrents (steep small mountain streams) that constitute the sediment production zone of several large fluvial systems. Torrent activity contributes to the regulation of the sediment regime of piedmont rivers whose morphological attributes are largely controlled by the upland sediment supply, as exemplified by the development of braiding patterns during the Little Ice Age (Bravard 1989). In the present-day context of accelerated channel incision of alpine rivers (Piégay and Stroffek 2000), it becomes imperative to better understand the nature and causes of fluctuating geomorphic activity in small mountain streams. The long-running debate in France about the origin of the alpine torrent crisis (increasing geomorphic activity in alpine environments) of the nineteenth century (Lenoble 1923; Mougin 1931) is relevant here, the principal issue being to discriminate between anthropogenic and climatic forcings in the torrent response.

Several approaches have been proposed to characterize changes in torrent activity through time. The reconstruction of flood histories from archives (Bravard 2000), assessment of changes affecting alluvial fan or active channel surfaces (Liébault et al. 1999; Gomez-Villar and Garcia-Ruiz 2000), and dating of torrential landforms (Kotarba 1989; Strunk 1997) all provide evidence concerning the changing nature of torrents on historical timescales. Some of these studies highlighted a major attenuation of torrent activity during the twentieth century. This evolution is often presented as the result of a combination of environmental changes that has led to increased stability in upland geomorphic systems. Some of these forcings are human-induced (land-use changes after rural depopulation and erosion-control schemes); others have climatic origin (the climatic transition following the Little Ice Age). The evaluation of the respective roles of these forcings is an important issue, because it will dictate our ability to predict channel response to future land-use or climate changes.

In this paper, the case of the Sure Torrent, an upland, gravel-bed stream located in the Southern French Prealps, is considered. Twentieth century channel response is examined in relation to a detailed analysis of basin-scale forcing. The main objective is to compare the nature and timing of basin-scale and reach-scale changes in order to give an interpretation of the twentieth century alpine torrent stabilisation.

THE STUDY SITE

The Sure Torrent is a right-bank tributary to the Drôme River, which drains an alpine Mesozoic sedimentary range (Diois) included in the Southern Prealps geological unit (Fig. 1A). This region is characterized by a major geological contact between the massive limestone mountains of the Vercors to the north and the highly folded marly slopes of the Diois to the south. The 72 km, drainage basin of the Sure Torrent corresponds to a large indentation cut through the southern piedmont of the Vercors.

An elongated configuration defines a classic torrential system with three important upstream sediment production zones: the Infernet, Colombet and Buchillet sub-basins (Fig. 1B, Photo 1). They consist of large erosion amphitheatres affected by a combination of active hillslope processes including gullying, surficial landsliding, debris flows and rockfall. Subsidiary sediment sources are present in some lower sub-basins, where active gullies are developing in interbedded layers of marl and limestone. The climate is characterized by Mediterranean influences. Maximum rainfall occurs during autumn and spring. Mean annual rainfall is ≈ 900 mm. The present-day population density is low, with only 314 inhabitants in the watershed or 4 inhabitants per square kilometre. The predominant vegetation type is a mixed forest cover, mainly composed of Austrian Black Pines (Pinus nigra) and Redwood (Pinus sylvestris).

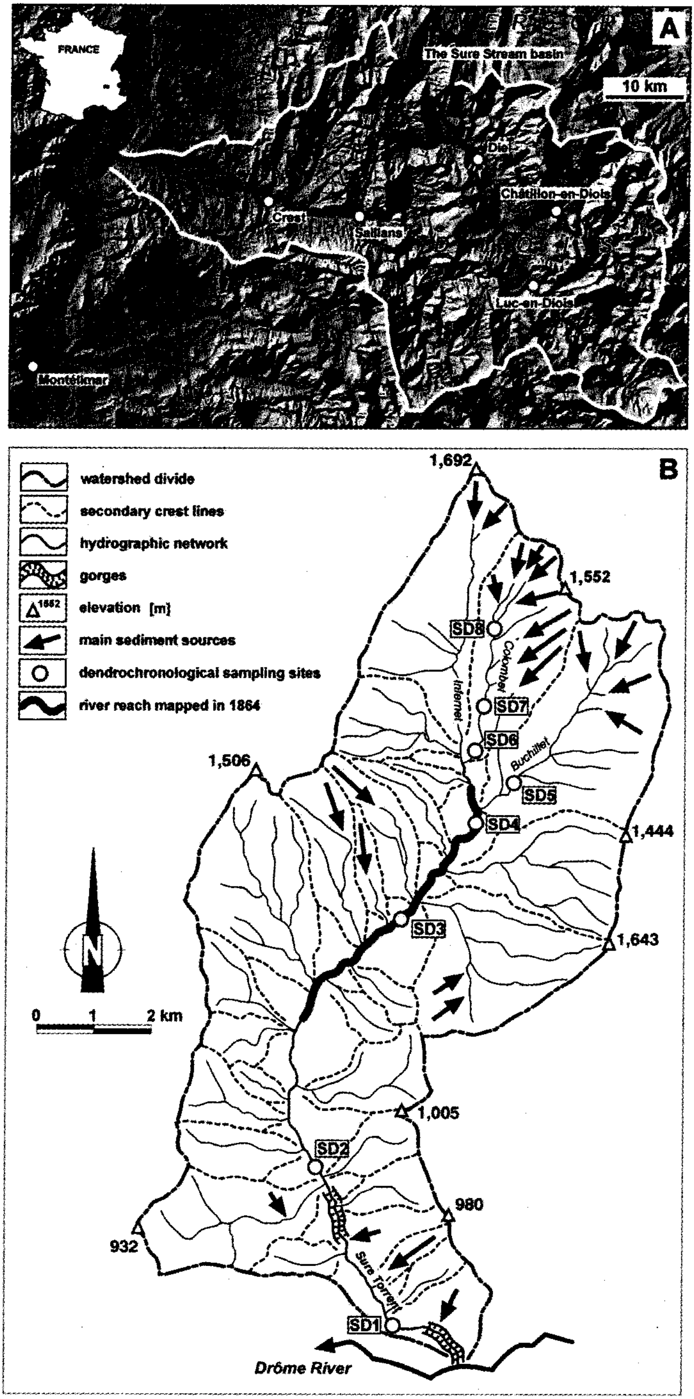

Fig. 1. The study site. A — shaded relief map of the Drôme River basin showing the general physical context of the Sure Torrent. B — synthetic map of the Sure Torrent watershed

Photo 1. Headwaters of the Sure Torrent watershed. Note the massive 200 meters thick Cretaceous limestone ridges of the Vercors overhanging active scree slopes in the background and the mid-slope erosion amphitheatre of the Colombet sub-basin in the foreground, with interbedded layers of Jurassic marl and limestone

Table 1

Physical attributes of the Sure Stream an its drainage basin (from 1 : 25,000 topographic maps, DEM 1 : 50,000 geological maps, 1991 aerial photographs)

Drainage basin [km^2]	72.47
Geology	marl and limestone
Maximum elevation [m]	1,692
Mean elevation [m]	800
Relief ratio	0.09
Annual rainfall [mm]	900
Stream order*	4
Channel slope [m · m^{-1}]	0.017
Active channel width [m]	12
Valley floor width [m]	180
Channel pattern	wandering gravel-bed river
$Q_{1.5}$ [m^3 · s^{-1}]	≈ 9

* According to the Strahler ordination method, applied to 1 : 100,000 topographic map

Agricultural activity is concentrated in the valley floor, where flat surfaces are occupied by pastures and ploughed fields.

The Sure Torrent is a fourth order, steep (0.017 $m \cdot m^{-1}$), gravel-bed river, with a main channel length of 12 km (Table 1). It is characterized by a predominant wandering pattern, alternating with braided and single-thread planned bed reaches. Two narrow gorges are present along the lower water course, where the river develops typical step-pool sequences (Fig. 1B). These gorges induce a geomorphic disconnection between the Sure Torrent and the Drôme River, making recent channel adjustments of the tributary independent from base-level changes. Thus, it is assumed that twentieth century incision along the Drôme River (Landon et al. 1998) has not induced subsequent knickpoint progression along the Sure Torrent, and indeed, no evidence of headward erosion was observed. The hydrological regime is influenced by snowmelt floods during Spring and Mediterranean storm floods during autumn. The stream is ungaged, but the mean annual flood can be estimated at $\approx 9\ m^3\ s^{-1}$, according to a regional flood frequency analysis (Liébault 2003).

MATERIAL AND METHODS

ACTIVE CHANNEL WIDTH EVOLUTION

Contemporary channel changes of the Sure Torrent were investigated by means of an 1864 map and five sets of aerial photographs dating back to 1948 (Table 2). The map, kept in the Departmental Archives of Valence (reference: AD 57S48), was produced in 1864 by the hydraulic service of the "Ponts-et-Chaussées" administration. This map was part of an embankment project concerning a 5,395 m reach located in the middle part of the basin (Fig. 1B). The large-scale mapping provides excellent information about the nineteenth century channel morphology (Fig. 2) and was used to measure the active channel width at 50 m intervals. The same procedure was performed on the 5 sets of air photographs in order to evaluate changes of active channel width during the 1864–2001 period.

Table 2

Documents used to reconstruct contemporary active channel changes of the Sure Torrent

Document	Date	Scale	Type
Old map	1864	1 : 1,000	Embankment project plan
Aerial photographs	1948	1 : 28,000	Black and white
Aerial photographs	1956	1 : 25,000	Black and white
Aerial photographs	1972	1 : 15,000	Infrared black and white
Aerial photographs	1991	1 : 17,000	Infrared colour
Aerial photographs	2001	1 : 25,000	Black and white

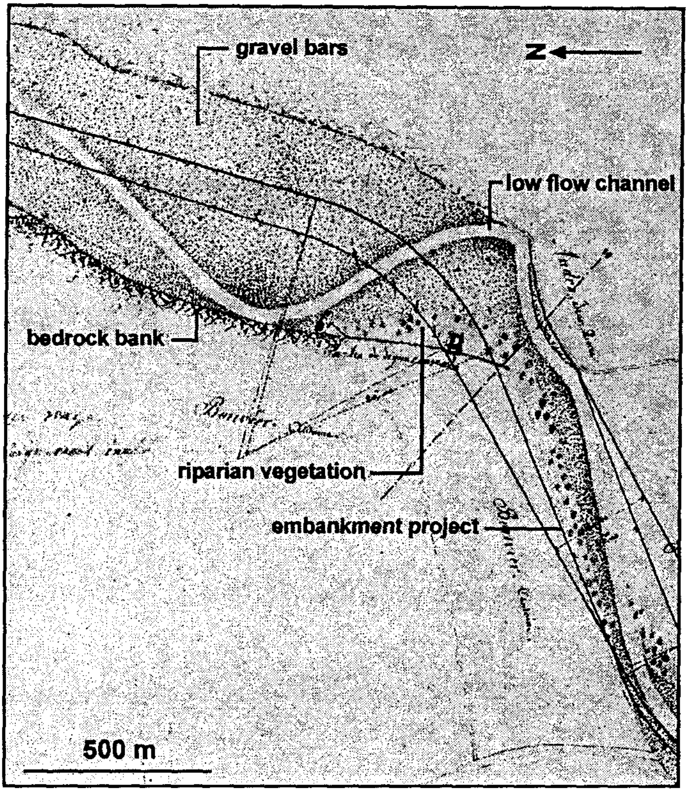

Fig. 2. Excerpt of the 1864 map of the Sure Torrent established by the hydraulic service of the "Ponts-et-Chaussées" administration. Note the level of detail of the mapping survey, clearly distinguishing active gravel bars from adjacent riparian vegetation patches. This map was used to plan the layout of an embankment project

The map and air photographs were not orthorectified because the objective was not to overlay the layouts of the channel planform at different dates, but to collect diachronic data on active channel width. The documents were scanned at a high resolution (900 dpi) in order to be digitally processed. The scale of each photo was defined as the average of 5 measurements between different reference points located on the valley floor. The photographs were then georeferenced using GIS software (MapInfo) in an arbitrary georeferencing system. The river course was digitized and measurement positions were automatically located at 50 m intervals. Active channel width was measured at each of these positions perpendicular to the thalweg. This procedure was previously tested by comparing field and 1 : 25,000 photo channel widths in some tributaries to the Drôme River and the mean difference was only 2.4 m ± 1.99 (Liébault 2003). Ninety percent of the differences were lower than 5.2 m. Channel widths measured on aerial photos were generally smaller than field-measured widths, which is attributed to the obscuration of channel boundaries by riparian vegetation.

A Mann-Whitney test was performed to characterize differences of channel width between dates. This statistical procedure was the most appropriate to our dataset, composed of 4 groups of 2 independent variables with non-normal distributions (Saporta 1990).

DENDROCHRONOLOGIAL DATING OF LOW TERRACES

Previous studies conducted in the Southern Prealps about contemporary channel changes in small mountain streams have highlighted that the dominant geomorphic response during the twentieth century was the formation of wooded low terraces along most of the torrents (Liébault and Piégay 2002; Liébault et al., in press). These terraces are present along the Sure Torrent and the riparian vegetation that established on these surfaces is well-preserved in several reaches. Eight sites, characterized by active channel narrowing and by well-preserved forest were selected for dendrochronological sampling with the aim of evaluating the chronology and spatial pattern of terrace formation process (Fig. 1B). At each site, cores were obtained from between 20 and 30 trees drawn from the older pioneer species established on recent terraces adjacent to the present active channel (Pinus sylvestris, Populus nigra, Populus alba, Salix eleagnos). All of these species generally encroach open dry surfaces (Rameau et al. 1993) and are therefore considered to be good chronological indicators for dating channel incision. A total of 209 trees were cored at 1.3 m height using an increment borer. Rings were counted manually after sanding down the wood cores as recommended by standard dendrochronological sampling procedures (Stokes and Smiley 1968; Strunk 1997).

Age distributions of pioneer species were compared between sites to highlight the longitudinal pattern in the timing of the establishment of riparian forest. The arithmetic mean age of the 5 oldest trees provides a minimum estimate for the initiation of terrace formation along the Sure Torrent. This approach is similar to the general procedure for lichenometric dating of geomorphic surfaces (Helsen et al. 2002). A linear regression model describing the relationship between this minimum age and distance downstream provides a means of evaluating the rate of progression of channel incision. The statistical quality of this model depends on two prerequisites: 1) the absence of human disturbance on the riparian forest; 2) the existence of a single terrace tread associated with a single channel response.

BASIN-SCALE FORCINGS

Changes in basin-scale environmental forcings were examined to aid interpretation of the spatial and chronological pattern of channel response. Previous studies conducted in the Southern Prealps have identified three important forcings since the end of the nineteenth century: 1) the climatic change following the end of the Little Ice Age; 2) the ambitious programme of torrent-control works conducted by the French Forest administration from 1860 onwards; and 3) strong rural depopulation following the end of World War Two and its effect on landscape reforestation (Liébault and Piégay 2002; Bravard and Landon 2003; Piégay et al. 2004).

An exhaustive programme of torrent-control works (RTM works, *Restauration des Terrains en Montagne*) was completed in the Sure Torrent watershed, including reforestation of hillslopes (mostly planting of Austrian Black Pine) and channel stabilization in headwater tributaries using check-dams, fascines, wattlings and brush gully checks. The archives of the National Forest Office record works done annually in each RTM zone (lands purchased by the Forest Administration for erosion mitigation) and therefore allow the chronology and spatial distribution of regulation works to be determined (Liébault and Zahnd 2001). This was done for the 4 RTM zones of the Sure Torrent watershed (Saint-Andéol, Saint-Julien-en-Quint, Sainte-Croix and Vachères-en-Quint). A National Forest Office survey of 1964 ("*enquête RTM*") was also consulted to obtain the definite reforested surface, taking into account the fact that some of the initial coniferous plantations were unsuccessful. This relatively old survey is sufficient for this purpose because reforestation works stopped after the First World War.

Land-use changes since the beginning of the nineteenth century were documented for the Sure Torrent watershed and in particular, they provide a clear indication of the evolution of forest cover between 1825 and 1991. Available resources include the 1825 Napoleonic land survey, agricultural surveys of 1929 and 1954, and the National Forest Inventory of 1991, which specify areas occupied by different types of land-use at the administrative scale of the municipality. Further information on these documents can be obtained in F. Taillefumier and H. Piégay (2003). Since no hydrological or climatic records are available for the Sure Torrent watershed, the evaluation of changes that affected the climatic forcing for the contemporary period is based on previously published studies for the Southern Prealps. These are based on available long records in the Drôme River basin (Landon 1999; Piégay et al. 2004) and archival evidence of extreme events (Bravard 2000) across the region.

RESULTS

ACTIVE CHANNEL NARROWING

The active channel of the Sure Torrent narrowed significantly during the second half of the twentieth century (Fig. 3). Most of the active gravel bars visible on 1948 or 1956 air photos are now occupied by a dense riparian forest. In-channel vegetation encroachment has been so pronounced in some reaches that the active channel is no longer visible in 1991 photos. Field reconnaissance of these reaches revealed that they correspond to narrow plane-bed channels, in the sense of the definition proposed by D. R. Montgomery and J. M. Buffington (1997) in their mountain stream classification. The channel adjustment depicted by multi-date air

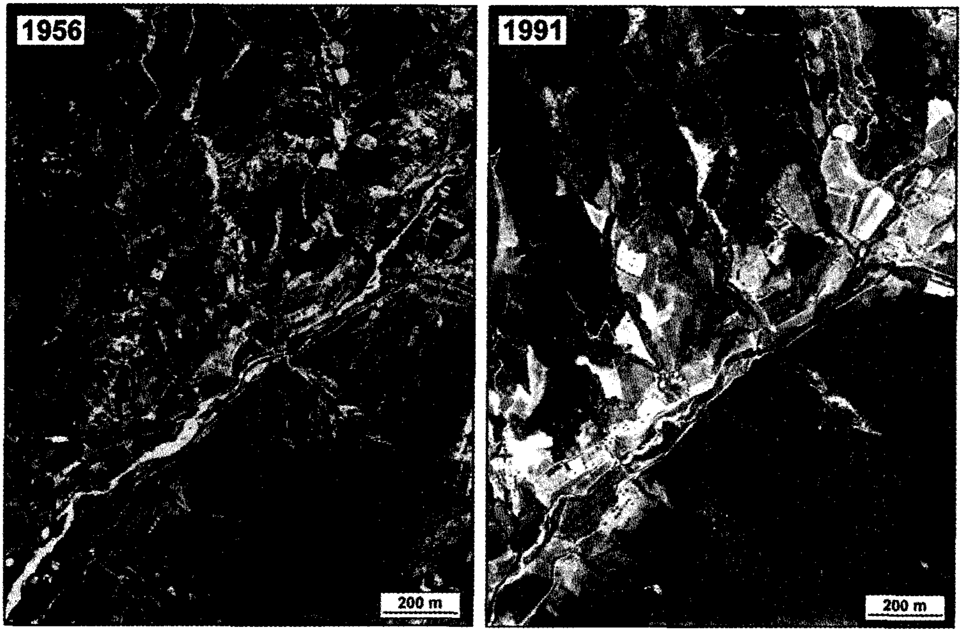

Fig. 3. Active channel narrowing of the Sure Torrent during the second half of the twentieth century illustrated by multi-date aerial photographs. The Sure Torrent flows from the top to the bottom of the photographs

photos can be considered as a channel metamorphosis, leading to the transformation of a former braided system into a wandering single-thread channel.

A general trend of channel narrowing was established for the central course of the Sure Torrent during the 1864–2001 period (Fig. 4). The mean active channel width decreased from 48 m in 1864 to 15 m in 2001. The average rate of channel

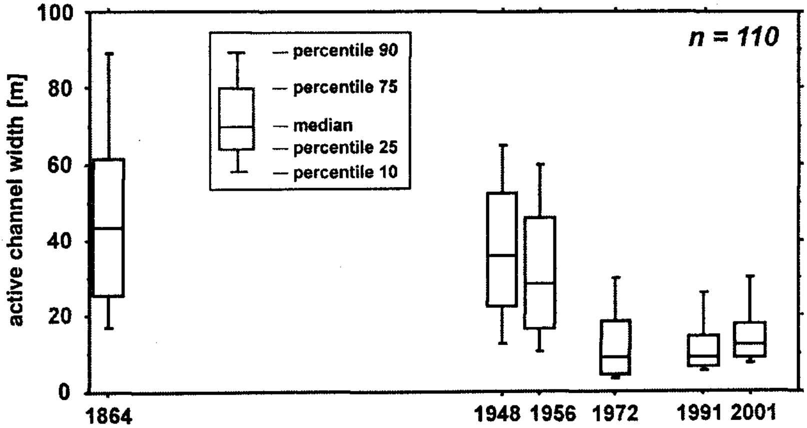

Fig. 4. Distributions of active channel widths measured at 50-m intervals along the Sure Torrent for different dates (see Fig. 1B for the location of the studied reach). n — number of observations

narrowing for this entire period is 69%. This corresponds to a time-averaged width decrease of 0.24 m · yr^{-1}. A strong acceleration of the adjustment is observed between 1956 and 1972, with a narrowing rate of 1.25 m · y^{-1}. The channel response takes a common exponential form, with attenuation of the change after 1972 and a narrowing rate of only 0.05 m · yr^{-1} between 1972 and 1991. Mann-Whitney non-parametric statistical tests revealed significant changes of channel width for the 1864–1948, 1956–1948 and 1956–1972 periods. Respective p-values are 0.0179, 0.0491 and < 0.0001 at the 95% confidence level. The test performed for the 1972–1991 period revealed non-significant changes (p-value of 0.2522) and the active channel width of the Sure Torrent can be considered as stable between 1972 and 1991. A small significant increase of channel width is observed for the 1991–2001 period ($p < 0.0001$). This can be attributed to the effect of a 100 yr RI flood that occurred in 1994 in the Drôme River basin.

The channel width adjustment presents a contrasting pattern through space and time, as illustrated by the longitudinal diagrams of channel change for different periods (Fig. 5). Channel narrowing was observed only upstream of km 9.8

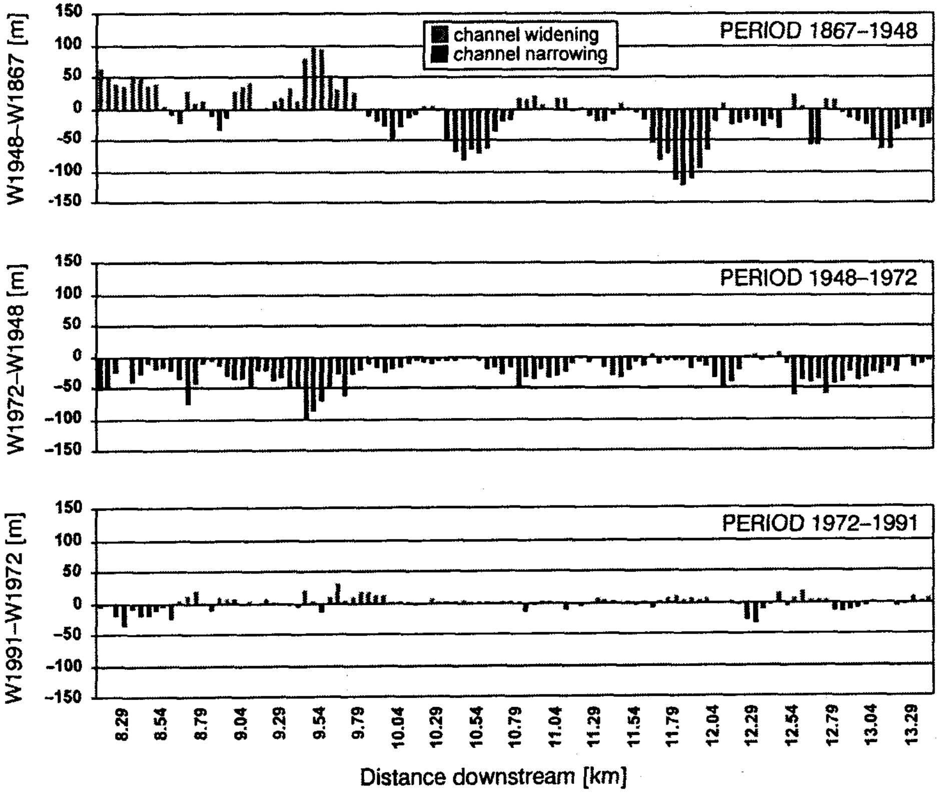

Fig. 5. Longitudinal patterns of change in active channel widths for different periods. W — denotes active channel width at the indicated date (see Fig. 1B for the location of the studied reach)

between 1864 and 1948, whereas channel widening prevailed for the downstream end of the reach. The situation is different for the 1948–1972 period, with a generalised and strong trend towards narrowing for the entire reach. This period is characterized by a peak value of width decrease near km 9.5. The final period shows relative stability without any significant cross-sectional adjustment throughout the reach. These observations suggest an upstream-driven channel response that has to be confirmed by the dendrochronological dating of low terraces. Moreover, it is probable that the degradation in headwaters induced temporary aggradation in downstream reaches until they became affected by the incision process. This can explain the active channel widening of the Sure Torrent observed downstream of km 9.8 between 1864 and 1948.

TERRACE FORMATION

Dendrochronological dating along the Sure Torrent revealed that the formation of low terraces occurred between the beginning of the 1920s and the end of the 1960s (Fig. 6). The range of tree ages obtained for the whole sample is 19–90 years, with a mean value of 38 ± 13 yrs. This indicates that the process of forest encroachment along the torrent was not synchronic in space and a chronological pattern of forest establishment along the water course is clear in Figure 6. Upstream riparian forests are older than those downstream, and a gradient of forest establishment appears between sampling sites that confirms an upstream-driven process of terrace formation.

The lag time of forest establishment between sites can be considered as an indicator of the downstream progression rate of the channel response. The lag time is more pronounced for upstream sites. This indicates a slower migration of the channel response through the headwaters. A value of 214 m · yr^{-1} is obtained between SD8 and SD4 (the upstream torrential reach), according to the 90th percentiles of tree ages, whereas a value of 568 m · yr^{-1} is obtained be-

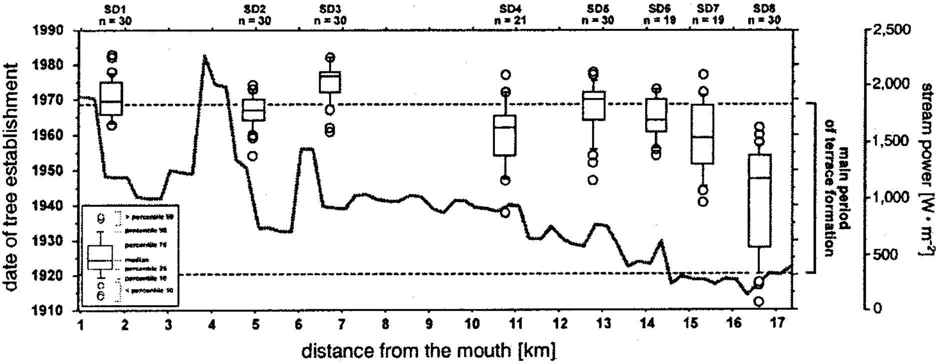

Fig. 6. Distributions of the dates of tree establishment on low terraces versus distance from the mouth of the Sure Torrent. n — number of cored trees. The grey line indicates the longitudinal variation of stream power for a $Q_{1.5}$ flood. The longitudinal pattern of tree establishment indicates an upstream-driven process of terrace formation

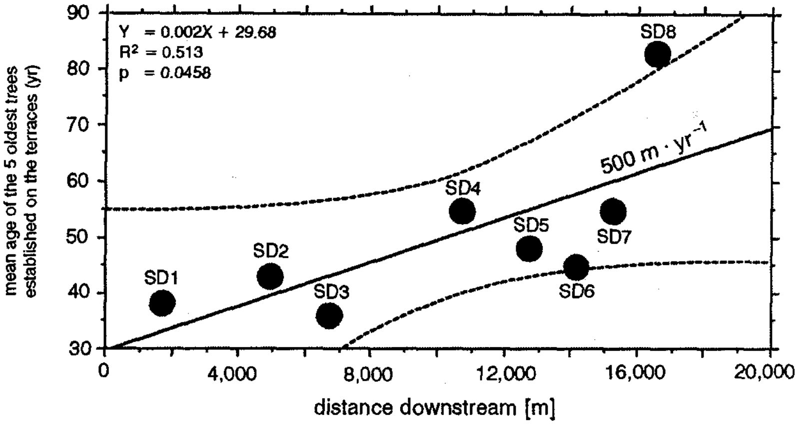

Fig. 7. Relationship between the mean age of the 5 oldest trees established on low terraces and distance downstream. The regression model indicates a downstream progression rate of terrace formation of 500 m · yr^{-1}. Dashed lines represent the 95% confidence levels on the regression model

tween SD4 and SD1 (the downstream fluvial reach). This difference is partly explained by the longitudinal variation of stream power (Fig. 6), which was roughly evaluated by means of 1 : 25,000 topographic maps. Valley-floor slope and drainage area were measured at 250-m intervals along the river course. A regional statistical relationship between $Q_{1.5}$ flood discharge and drainage area (Liébault 2003) was used to evaluate water discharges. Acceleration of the migration rate occurs within reaches characterized by higher stream power. This is observed downstream of km 14.5, where the stream power starts to increase due to the water supplies coming from the Infernet and Buchillet tributaries. The fast migration rate observed downstream of km 5 can also be linked with an increase in hydraulic energy, SD2 and SD1 being separated by a steep-gradient gorge which may have accelerated the propagation of the channel response.

A significant linear regression model ($\alpha = 0.05$) describes the relation between the mean age of the 5 oldest trees growing on low terraces and the distance downstream (Fig. 7). This model indicates an average downstream progression rate of terrace formation of 500 m · yr^{-1}. Two sampling sites alter the model and show high residuals: SD8 (20.26) and SD6 (–12.98). Both sites are located along the Colombet Torrent and their riparian forest may be more influenced by individual debris flows triggered by extreme events. It is also possible to imagine a human-disturbance (forest clearance) on the SD6 site, which may explain a forest composition which is younger than expected.

ENVIRONMENTAL CHANGES

Three RTM zones, occupying 27% of the drainage basin, were established in the Sure Torrent basin at the end of the 1890s: Sainte-Croix, Saint-Julien-en-Quint and Vachères-en-Quint (Fig. 8). Regulation works started respectively in 1905, 1899 and 1902. Their locations coincide with the location of the main sediment sources of the Sure Torrent (Fig. 1B). The common procedure followed by the French Forest administration of the nineteenth century was to focus RTM projects in the most eroded headwater sub-basins and then to implement procedures for land acquisition (Demontzey 1882). The absence of an RTM zone in the Saint-Andéol municipality suggests that headwaters in this area were not very active at the end of the nineteenth century; a situation that persists today. Most of the gullies where works were completed are located in the Infernet and Colombet sub-basins (Fig. 8). The inventory of RTM works (Table 3) indicates the extent and significance of these erosion-control measures which were mainly completed between 1899 and 1917 (Fig. 9). Given the type of works done, it can be assumed that erosion rates have been attenuated on hillslopes by reforestation and turfing, and that a substantial amount of sediment has been trapped in headwater channels by check-dams and wattlings (small grade-control structures made of wood). An evaluation of the amount of sediment stored behind 8 check-dams along the Infernet Torrent gave a volume of 2,300 m^3 (Liébault and Beullens 1997). Brush-gully checks (use of brush mulchin or fascines in gullies to aid in revegetation) along more than 5 km of channels have probably helped to stabilise some low order gullies.

The Sure Torrent basin has experienced considerable land-use changes during the last two centuries. Land-use statistics show that the forest cover increased from 32% in 1825 to 81% in 1991 (Table 4). Most of the forest cover increase occurred during the second half of the twentieth century, at a rate of 71 ha · yr^{-1} between 1954 and 1991. The corresponding value for 1825–1929 is 15 ha · yr^{-1}. A slight decrease in forest cover is observed between 1929 and 1954 but it is not clear whether this decrease corresponds to a real phenomenon because agricultural surveys are prone to some uncertainties and it is not always possible to make rigorous comparisons between dates (Taillefumier 2000). Nevertheless, we can affirm that the reforestation during the first half of the twentieth century was low as compared to earlier and later periods.

Archives from the National Forest Office reveal that 562 ha of forest were planted between 1900 and 1978 (Table 3). The 1964 RTM survey reports reforestation of 680 ha in the three RTM zones of the Sure Torrent since 1900. We can consider that this reforestation occurred mainly before 1929, given the chronology of RTM works (Fig. 9). Thereby, planned reforestation represents 44% of the total forest progression between 1825 and 1929 (1,526 ha according to data presented in Table 4), whereas post-1954 forest establishment has to be attributed to the rural depopulation effect. Census data for the 4 municipalities included in the Sure Torrent basin show that the population has decreased by 77% from 1,376 inhabitants in 1831 to 314 inhabitants today (Daumas 1999). The subsequent decline of grazing and field abandonment, mainly occurring after World War Two, resulted in extensive natural forest regeneration. We can estimate that 82% of the total forest progression for the 1825–1991 period (3,750 ha according to data presented in Table 4) was directly driven by the rural depopulation effect.

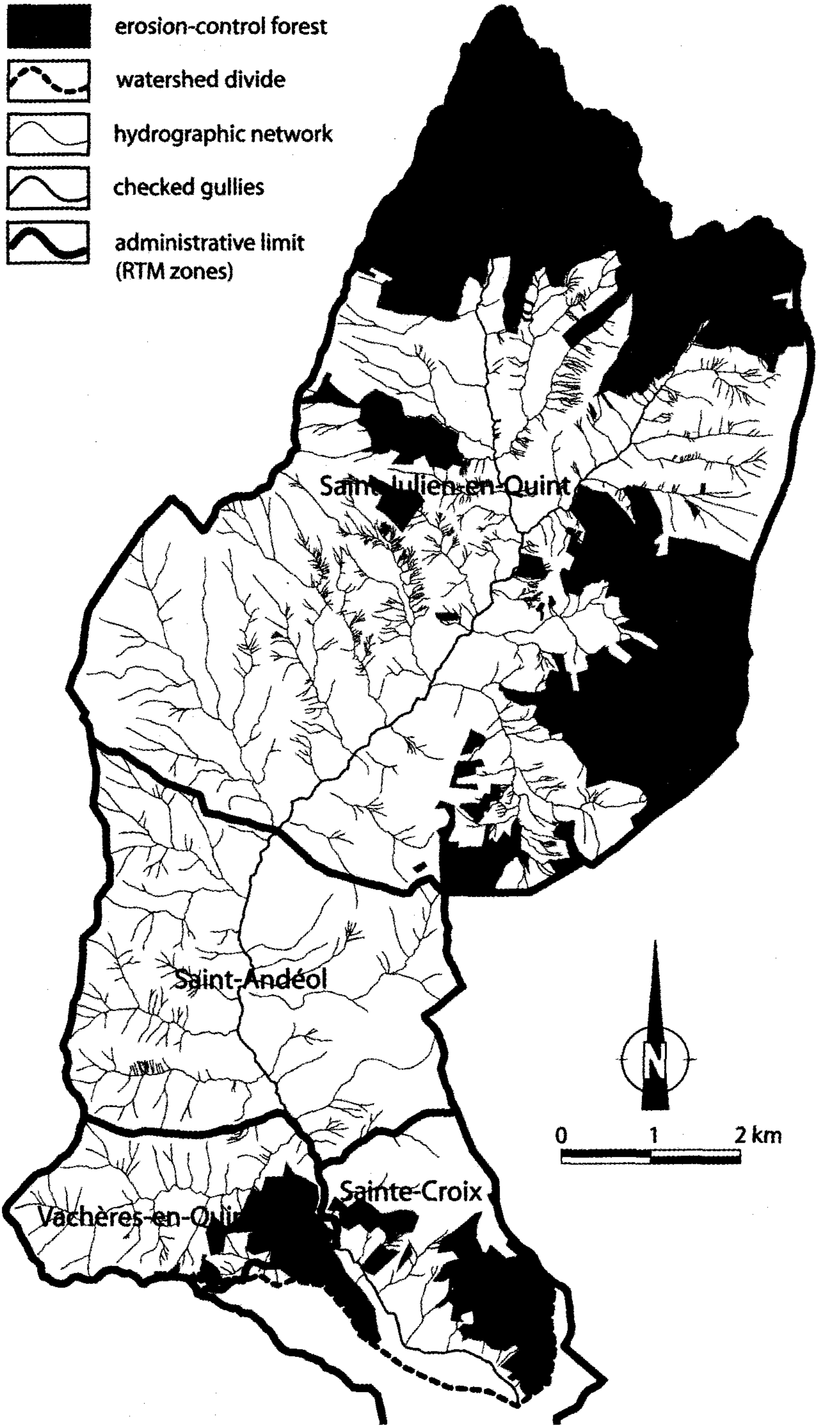

Fig. 8. Map of the RTM zones established in the Sure Torrent basin

Table 3

Torrent control works conducted in the Sure Torrent basin between 1899 and 1978 (data from the National Forest Office archives)

RTM zones	Saint-Julien-en-Quint	Sainte-Croix	Vachè-res-en-Quint	TOTAL
Erosion-control area [ha]	1,571	265	94	1,930
Turfing (kg of seeds)[1]	1,228	251	200	1,679
Planting [ha]	423	83	56	562
Wattlings (number)[2]	290	0	0	290
Check-dams (number)	28	22	0	50
Brush gully check [m][3]	4,349	331	810	5,490

1 — Use of grass to aid in revegetating bare surfaces

2 — Small check-dams made of wood, implanted on low-order headwaters

3 — Use of brush mulchin or fascines in gullies to aid in revegetation

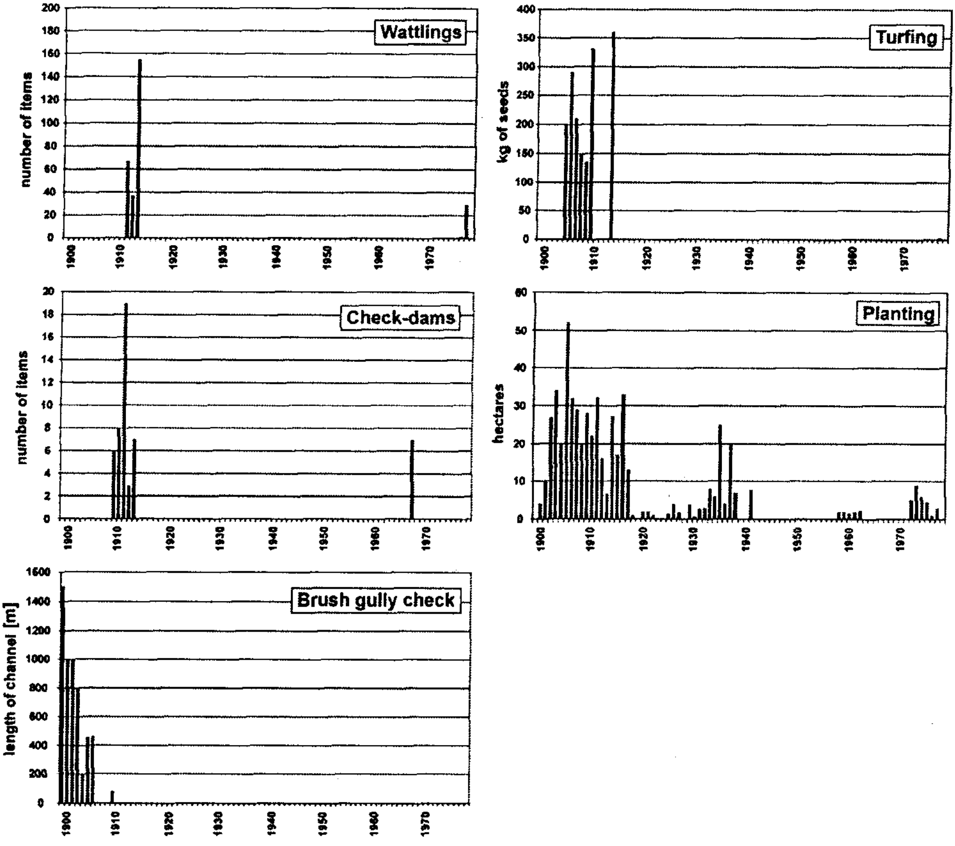

Fig. 9. Chronology of torrent-control works conducted in the Sure Torrent basin between 1899 and 1978 (data from the National Forest Office archives)

Table 4

Forest cover changes in the Sure Torrent basin during the 1825–1991 period from land-use statistics

Administrative units	1825 forest cover [ha][1]	1929 forest cover [ha][2]	1954 forest cover [ha][2]	1991 forest cover [ha][3]	Erosion--control re-forestation [ha][4]
Saint-Andéol	638	900	957	1,116	0
Saint-Julien-en-Quint	1,309	2,233	1,777	3,835	500
Sainte-Croix	306	618	541	826	120
Vachères-en-Quint	234	262	337	460	60
TOTAL [ha]	2,487	4,013	3,612	6,237	680
TOTAL [%]	32	52	47	81	9

1 — Napoleonic cadastre
2 — Agricultural land survey (enquêtes agricoles)
3 — National Forest Inventory (Inventaire Forestier National)
4 — 1964 National Forest Office Survey (enquête RTM)

Contemporary climate changes for the Sure Torrent basin are not known, because there are no long-term weather or gauging stations in this area. Nevertheless, if it is assumed that the climatic history of the Sure Torrent is similar to those changes and extreme event sequences that characterize the Diois Mountains, then it is likely that: 1) there was an increase in the frequency of extreme rainfall events between 1840 and 1866; 2) a reduced frequency of floods between 1940 and 1990; and 3) an increased frequency of large autumn floods since the 1990s (Landon 1999; Bravard and Landon 2003; Piégay et al. 2004).

DISCUSSION

The Sure Torrent experienced significant stabilisation during the twentieth century, as attested by narrowing of the active channel and rapid formation of low wooded terraces. These channel adjustments, leading to a channel metamorphosis from braiding to wandering or meandering patterns (Schumm 1969), have been observed elsewhere in the Southern Alps (Gautier 1992; Piégay and Salvador 1997; Liébault and Piégay 2002; Flez and Lahousse 2003) but also in the Spanish Pyrenees (Garcia-Ruiz et al. 1997) and in Tuscany (Surian and Rinaldi 2003). Of considerable scientific interest is the relative influence of climatic and anthropogenic forcings in driving this geomorphic response. What can be said about this after examining information collected on the Sure Torrent?

The torrent response clearly reflects channel adjustment to reduced sediment supply from the headwater sub-basins. This could be associated with a change in the sediment regime of the torrent or a change in its hydrological regime, particularly the reduced incidence of flood events after the 1940s. The upstream-driven terrace formation process is a strong evidence that modification of the sediment regime is of primary importance. If a hydrological explanation was correct, synchronic channel narrowing would be expected along the water course (Liébault and Piégay 2002), but here both dendrochronological dating and historical reconstruction of channel changes demonstrate asynchronous, downstream propagation of channel narrowing and terrace formation. We must therefore consider the channel narrowing of the Sure Torrent as the result of a degradation process leading to the formation of a new narrow channel incised into a former braided active plain. This type of adjustment has already been described in a semi-arid stream channel adjusting to the spontaneous reforestation of hillslopes following wildfire (Germanoski and Harvey 1993).

Several environmental factors can account for the apparent reduction in sediment supply during the twentieth century. RTM works conducted in the headwater zones stabilized sediment sources, as shown by the analysis of ground-based photography (Liébault and Zahnd 2001). The chronology of these works shows that they were implemented between 1899 and 1917. Dendrochronological dating of low terraces shows that they begin to form in the 1920s. It is then possible to link RTM works with the beginning of the channel incision, as observed in neighbouring basins (Piégay and Salvador 1997; Piégay et al. 2004). Nevertheless, it is difficult to consider that RTM works induced the strong acceleration of the channel narrowing observed from the 1950s onward. Given the high geomorphic sensitivity of mountain streams and the strong hillslope-channel coupling of the Sure Torrent in its upstream basin, a short response time is expected (Harvey 2001). However, the 50-year lag time between the period of regulation works and the accelerated channel response suggests that another forcing factor is also important. The most evident is the spontaneous reforestation of hillslopes following rural depopulation during the second half of the twentieth century. Land-use statistics reveal a strong acceleration of forest establishment in the watershed since 1954. This land-use change can explain a substantial decrease of sediment supply, as demonstrated by several experimental studies of the effect of vegetation on sediment production in Mediterranean environments (Garcia-Ruiz et al. 1995; Cerda 1998; Mathys et al. 2003).

To what degree can the channel response of the Sure Torrent be linked with climate changes? Previous studies from the Southern Prealps highlighted a period of increased frequency of extreme rainfall events during the terminal period of the LIA between 1840 and 1866 (Bravard and Landon 2003). If it is assumed that this period was followed by a long-lasting attenuation of the climatic impulses up to the 1990s, as suggested by J. P. Bravard and N. Landon (2003), it is difficult to explain the chronological pattern of the torrent response, with a probable marked adjustment in the 1920s (first establishment of riparian forests) and a second one in the 1950s. Better chronological links are observed with the anthropogenic factors discussed above. Moreover, there is no substantial reduction in high-intensity rainfall events in the Drôme River basin during the second half of the twentieth century (Landon 1999), whereas this period corresponds to the major channel metamorphosis of the Sure Torrent, leading to the disappearance of braided landforms along most of the river course. To this day, then, climatic influence on the geomorphic signal of the Diois torrents during the twentieth century has not been demonstrated. The situation is different for the nineteenth century, insofar as strong links have been highlighted between storm-induced active hydrological periods and aggradation phases (Bravard and Landon 2003). However, it is probable that the nineteenth century channel responses were highly amplified by the deforested context that prevailed at that time and which prompted the RTM programmes.

Dendrochronological dating of twentieth century terraces revealed that the channel response propagated downstream in the form of an upstream-driven degradation process that travelled at a rate of 500 m · yr^{-1}. It is notable that this rate for the propagation of sediment starvation is similar to the range of sediment wave migration rates (60–1,000 m · yr^{-1}) observed in some gravel-bed rivers (Nicholas et al. 1995). According to the average rate it would take approximately 30 years for the Sure Torrent to achieve an adjustment induced by a change in sediment regime. Considering the chronology of RTM works and assuming that they were sufficiently important to induce a degradation phase along the entire river course, adjustment should have been complete by the 1950s. This provides further evidence that the post-1950 channel narrowing was not driven by RTM works. The same scenario can be applied to the spontaneous reforestation effect that accelerated after the World War Two. We can predict an achieved adjustment at the end of the 1970s. The pattern of active channel narrowing confirms this date, given the stability of the active channel width observed after 1971.

CONCLUSION

A detailed comparison of the timing and nature of channel responses and environmental forcings in the Sure Torrent confirms the sensitivity of upland fluvial systems to anthropogenic modification of forest cover on hillslopes. It has been demonstrated that both torrent-control works and spontaneous reforestation following rural depopulation have modified the sediment regime of the torrent and induced upstream-driven degradation processes that migrate downstream at an average rate of 500 m · yr^{-1}. Basin-scale forest establishment following abandonment of agricultural land had the greater effect, causing accelerated metamorphosis of the former braided pattern that was predominant in the landscape until the 1950s. This channel pattern can be considered as a relict landform, inherited from the geomorphic crisis at the end of the nineteenth century which saw elevated sediment delivery to torrent systems and in turn led to the establishment of remedial RTM works. Progressive replacement by single-thread, narrow and incised channels, has been widespread so that such channels are now the dominant torrent morphology in the Southern French Prealps.

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Laboratoire Environnement-Ville-Société
UMR 5600 du CNRS
18, rue Chevreul
69 362 LYON cedex 07
frederic.liebault@free.fr

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STRESZCZENIE

F. Liebault

MORFOLOGICZNA ODPOWIEDŹ ALPEJSKICH POTOKÓW NA PONOWNE ZALESIENIE ZLEWNI (POTOK SURE W POŁUDNIOWYCH PREALPACH FRANCUSKICH)

Reakcja zlewni górskich na ponowne zalesienie, spowodowane regulacją cieków i wyludnieniem obszaru po II wojnie światoej, jest przedstawiona w oparciu o dokumenty historyczne i datowania dendrochronologiczne na współczesnych terasach. Stwierdzono szybkie zmniejszanie szerokości koryt po roku 1950. Przystosowanie koryt do nowych warunków polega na ich wcinaniu i formowaniu teras wskutek zmniejszonej dostawy zwietrzelin do koryt w obszarach źródłowych. Koryta roztokowe dominowały w dnach dolin do roku 1950. Dzisiaj są formami reliktowymi, odziedziczonymi po geomorfologicznym kryzysie, który wystąpił z końcem XIX wieku. Obecnie dominuje formowanie pojedynczych, prostych koryt.