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CAUSES OF 20th CENTURY CHANNEL NARROWING IN MOUNTAIN AND PIEDMONT RIVERS OF SOUTHEASTERN FRANCE

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ABSTRACT

Extensive channel narrowing in southeastern France provides an illustration of geomorphic response to land-use changes. The study region comprises a range of environments, from large piedmont and intramountain gravel-bed rivers, to small mountain streams. Field measurements and analysis of historical data demonstrate two distinct periods of channel change. From 1850 to 1950, channel narrowing is interpreted to be the result of a recovery process in response to widespread channel destabilization induced by major floods during the second half of the 19th century. At the time, the largely deforested basins were highly responsive to flooding, whereas the recovery process was accelerated by floodplain and basin-scale land use changes (afforestation) and torrential control works, which in turn reduced sediment delivery and enabled vegetation development in channels. From 1950 to 1970, channel narrowing accelerated in most of the studied rivers. This recent phenomenon is considered as a human-induced fluvial adjustment, directly related to forest development on river margins and human abandonment of intensive floodplain land uses. At the same time, long-profile degradation occurred as a result of long-term bedload supply decrease. In small mountain streams, channel narrowing is mainly explained by channel incision which seems to progress from upstream where sediment sources are progressively stabilized by afforestation. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: channel width adjustment; active channel narrowing; riparian vegetation; incision; land-use change; hydrological change; mountain stream; gravel-bed river; France

INTRODUCTION

Rivers have been viewed as systems at least since Schumm's (1977) exposition of the complex links between control variables of bedload sediment supply, Q_s, and the discharge Q, and dependent variables of channel geometry. Research conducted on hydraulic geometry following Leopold and Maddock's (1953) pioneering work established power relationships between the discharge and channel pattern, depth, width, and meander wavelength. For example, empirical relationships have been established on several rivers to predict the channel width (W in m) from Q, the bankfull discharge (in $m^3\ s^{-1}$):

$$W = a\ Q^b \tag{1}$$

The importance of bedload sediment supply notwithstanding, channel geometry can be strongly influenced by local controls such as slope imposed by the geological setting, the vegetation cover of banks, and the grain size of the valley floor. Dense vegetation can increase roughness and, via binding effects of the roots, increase bank resistance to erosion. As a consequence, the coefficient a of the relationship between discharge and channel width (Equation 1) decreases when the vegetation cover is greater and more arboreous (Andrews, 1984; Hey and Thorne, 1986; Huang and Nanson, 1997). Herbaceous cover was found to be more effective than arboreous cover in maintaining narrow channels on small streams (Zimmermann *et al.*, 1967; Bergeron and Roy, 1985; Clifton, 1989; Trimble, 1997). The contrasting results demonstrate that vegetation plays a

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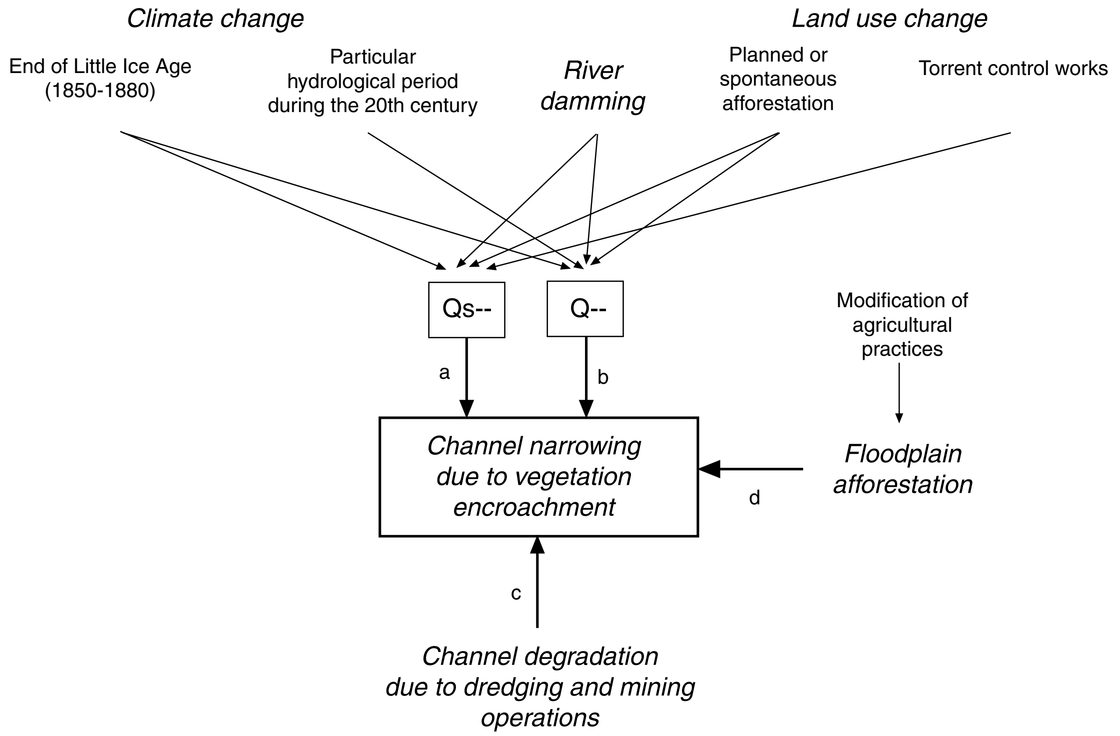

a : Qs decrease > Q decrease
i) dyschronism between Qs decrease and channel narrowing due to system response time to change (the response time is mainly related to the time of sediment transfer through the basin)
ii) progressive channel narrowing from the sediment sources

b : Q decrease > Qs decrease
i) synchronism between floodplain afforestation and channel narrowing

c : Hydraulic deconnection of former active surfaces by channel degradation
i) channel incision prior to vegetation encroachment in active channels
ii) progressive channel narrowing from locations where the bed is lowered (upstream and downstream progression of degradation from disturbed reaches)

d : Channel adjustment to floodplain afforestation
i) synchronism between floodplain afforestation and channel narrowing

Figure 1. Conceptual model of factors controlling channel narrowing: working hypothesis (a to d)

variable role depending on other parameters, such as bank height or sediment characteristics (Gregory and Gurnell, 1988).

Just as channel geometry can adjust over time in response to changes that affect bedload and discharge, it can also adjust to changes in bank and floodplain vegetation. Reservoir-induced peak flow reduction, bed sediment trapping, and resulting channel narrowing have been described by Eschner *et al.* (1983), Collier *et al.* (1996) and Peiry (1997). Examples of channel narrowing associated with decreased discharges include Schumm and Lichty (1963), and Friedman *et al.* (1996). Documented effects of vegetation change on channel form include channel widening after bank vegetation loss (Kondolf and Curry, 1986) and channel narrowing associated with vegetation development on channel margins (Hadley, 1961; Nevins, 1969; Graf, 1978). Cross-section adjustment to vegetation change is generally explained by the modification of bank roughness and resistance to erosion (Millar, 2000) or by the modification of in-channel sediment trapping efficiency which can induce floodplain construction in former active channels (Schumm and Lichty, 1963; Osterkamp and Costa, 1987).

European rivers have undergone complex adjustments during the last two centuries because human activities have influenced discharge, bedload supply and transport at different levels within the basins and in different periods. As a consequence, channel narrowing at different times and places has been interpreted in different ways. Channel shrinkage has been associated with effects of reservoirs and discharge modifications (Peiry and Vivian, 1994; Surian, 1999), floodplain land-use changes (Piégay *et al.*, 1994, in press), hydrological fluctuations (Miramont and Guilbert, 1997) or bedload supply decrease (Bravard and Peiry, 1993; Garcia-Ruiz *et al.*, 1997; Liébault and Piégay, 2001). If the first cause is easy to establish because of the strong chronological links existing between the dates of reservoir construction and consequent vegetation encroachment, the two others are more difficult to prove. They often occurred in the same basins and their respective influences on vegetation encroachment have still not been established.

The aim of this study is to review the different observations made on wide gravel-bed rivers and small streams in the mountains and piedmont of southeastern France to determine the respective influence of basin and valley-floor scale controls on the channel narrowing process (Figure 1). Based on the chronological and spatial patterns of channel and environmental changes in multiple basins in the region, the relative influence of natural and human factors on narrowing is assessed.

MATERIAL AND METHODS

A contrasted sample from catchment size and region concerned

A large set of rivers and streams located in southeastern France (Figure 2 and Table I) has been selected. These basins range in catchment area from 63 to 17 600 km^2 and span a wide range of climates (oceanic, continental and Mediterranean) and geomorphological environments (intramountain plains covering lacustrine or periglacial deposits, piedmonts). In the first instance, a comparison analysis on the large rivers in the data set (i.e. $>$450 km^2) is performed. Secondly, a detailed analysis on the Eygues, Roubion and Drôme basins is documented. These basins adjoin one another in the southern Prealps, a homogeneous geomorphic region of low-elevation limestone mountains. Field and archival data were collected from 51 tributaries to test chronological links between channel narrowing and basin land-use changes and/or channel regulation. These tributaries range from 10 to 150 km^2 in drainage area, from 450 to 1390 m in mean elevation, and from 0·008 and 0·03 m m^{-1} in slope. They all have floodplains that are sufficiently wide to allow lateral adjustment in their downstream reaches. These streams represent small fluvial systems with a strong coupling between hillslopes and channels in their upstream reaches, suggesting a high sensitivity to environmental changes.

Assessment of channel narrowing

Historical data (old maps and air photos) and dendrochronology were used to characterize and date contemporary changes in channel width and vegetation encroachment on formerly active alluvial surfaces. The widths of active channels (low-flow channels and unvegetated gravel bars) were measured on aerial photographs from the mid-1940s to the 1990s (scales range from 1 : 17 000 to 1 : 25 000) and on detailed maps and land surveys from the 19th century. On wide gravel-bed rivers, it was possible to measure active channel width for regularly spaced segments (generally 500 m in length). Investigated reaches ranged from 21 to 93 km in length and were generally selected on downstream parts of the basins. On small streams, active channel areas were measured in downstream reaches (all in alluvial portions of the streams) and mean channel width was calculated by dividing the active area by the length of the reach. Comparing measurements of active channel width from aerial photos and the field on two small tributaries of the Eygues showed that the air photos underestimated channel width because part of the channel was obscured by bank vegetation. The portion of channel obscured by bank vegetation was up to 10 m, with most values between 0 and 4 m, and a mean of 3·09 m (Liébault *et al.*, 2001). Thus, analysis of sequential air photos should be capable of detecting width changes of more than 3 m. A Mann–Whitney U-test was performed to characterize differences of channel width (non-normal distribution) between dates. An ANOVA test was performed to detect significant differences between rates of channel narrowing (normal distribution) obtained on tributaries of the Drôme, Eygues and Roubion rivers.

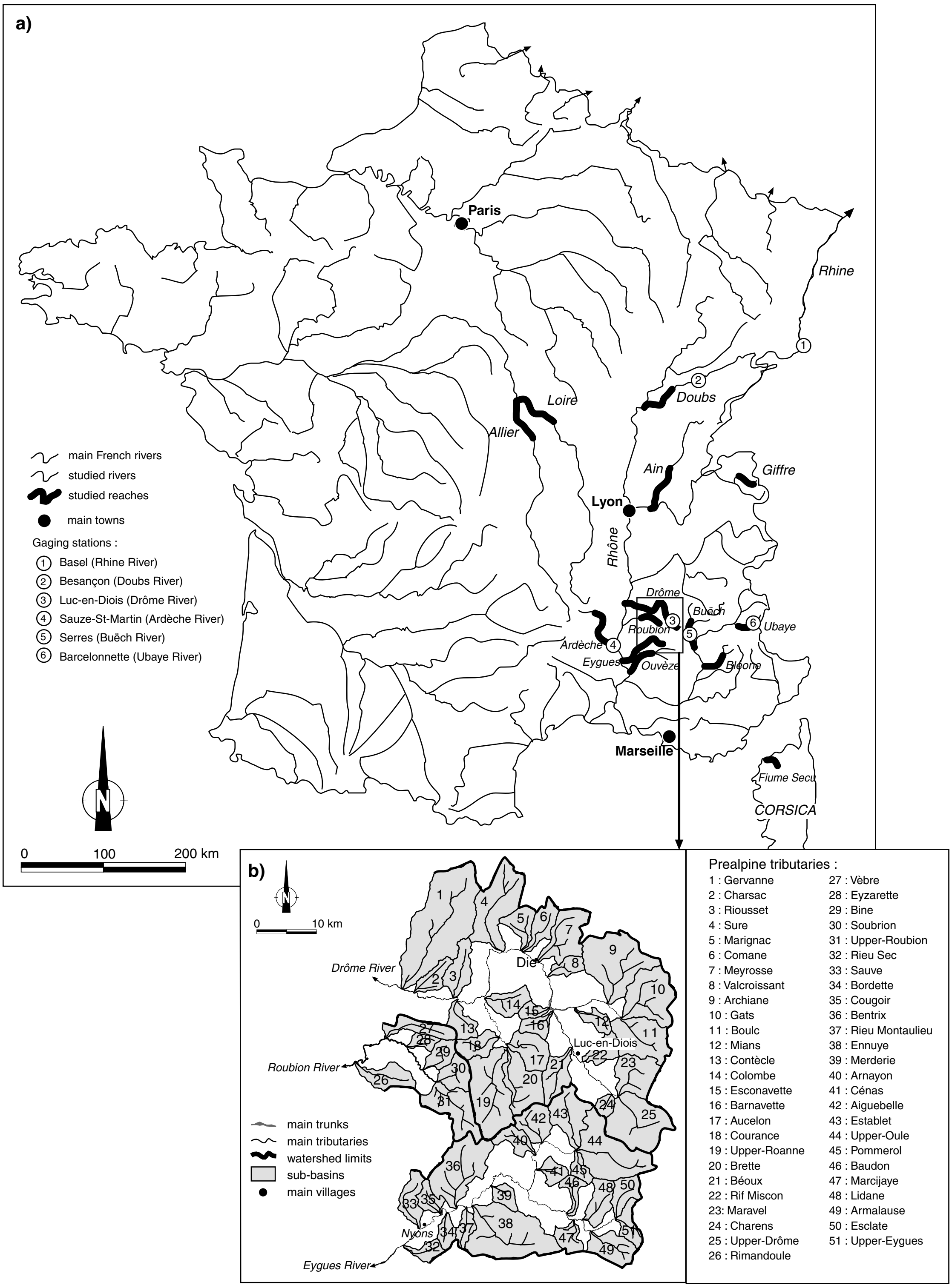

Figure 2. The study site: (a) location of large gravel-bed rivers studied; (b) detailed map of the selected southern Prealps small mountain streams

Table I. Main characteristics of studied rivers

Rivers	Drainage basin (km^2)	Max. elevation (m)	Geomorphological characters	Dam regulating floods (year of construction)	Mean annual discharge ($m^3\ s^{-1}$)	Reference
Ain	3630	1300	Free-meandering/piedmont	1968	122	Piégay (1995)
Ardèche	2240	1500	Single-bed sinuous river/piedmont	–	26	Piégay (1995)
Bléone	980	2819	Braided/inner southern Alps	–	9·2	Saulnier (1999)
Buëch	974	2709	Braided/southern Prealps	–	15	Gautier (1992)
Doubs	7700	1460	Anastomosing and meandering/piedmont	–	177	
Drôme	1642	2051	Braided/piedmont	–	19	Landon (1999)
Eygues	1150	1757	Braided/piedmont/M	–	6	Landon Piégay (unpublished work)
Fiume Seccu	63	2029	Single-bed sinuous river/M	–		Gaillot and Piégay (1998)
Giffre	459	3100	Braided/northern Alps	–	19	Piégay (1995)
Loire (upstream of Nevers)	17 570	1800	Wandering/piedmont	1984	185	Gautier *et al.*, (2000)
Allier	13 000	1800	Wandering/piedmont	–	160	Gautier *et al.* (2000)
Ouvèze	1818	1900	Braided/piedmont/M	–	5	Piégay (1995)
Roubion	600	1606	Single-bed sinuous stream/piedmont	–	2	Liébault and Piégay (2001)
Southern Prealps tributaries	10–150	2051	Single-bed sinuous streams/southern Prealps	–	<2	Liébault *et al.* (2001)
Ubaye	970	3000	Braided/inner southern Alps	–	11	Piégay (1995)

M, Mediterranean.

Trees were cored and rings counted for a total of 405 riparian trees established on the first vegetated surfaces adjacent to the active channels on both (i) wide gravel-bed rivers draining more than 900 km^2 (Drôme, Ain and Ubaye), and (ii) small mountain streams draining areas between 10 and 100 km^2 (Archiane, Béoux, Bine, Fiume Secu, Gats, Rif Miscon, Upper-Roubion). The oldest species present (*Alnus incana, Populus nigra, Pinus sylvestris*) were sampled to obtain a minimum date for establishment of the riparian forest.

Assessment of environmental changes

Modifications of environmental controls on channel morphology were examined at both the basin and reach scales to assess their respective influence. In addition, gauging records were analysed whenever long records were available.

Basin-scale controls included land-use changes on hillslopes and, in some areas, torrent control works conducted between 1860 and 1920 to stabilize sites of active erosion. Land-use modifications since the beginning of the 19th century have been documented in the Ouvèze, Ardèche, Ubaye, Eygues, Drôme and Roubion river basins. Resources utilized included Napoleonic land surveys for the period 1822–1840, agricultural surveys of 1929, 1954 and 1988, and the National Forest Inventory of 1991. These various sources all indicate areas occupied by different types of land use at the administrative scale of the municipality. An exhaustive inventory of torrent control works conducted in the southern Prealps was completed, including reafforestation of hillslopes (mostly planting of *Pinus nigra*), and channel stabilization in headwaters (check-dams, fascines and wattlings, brush gully checks). The archives of the National Forest Office recorded works done annually in each municipality, allowing determination of the chronology and spatial distribution of regulation works on torrents. Other written archives and historical statistics (population growth, grazing pressure, industrial activity) provided further information.

At the reach scale, floodplain land-use changes were documented using the Napoleonic land surveys (1820–1840) and more recent sources, such as aerial photos and recent land survey maps on the middle Ardèche, Ouvèze, Eygues, Drôme and Ain rivers (Piégay, 1995). Long-profiles surveyed in the 1920–1930s were compared with equivalent surveys from the 1980–1990s to evaluate vertical channel changes in most of the study streams (see details in Landon, 1999). Information on long-profile changes was also available on other basins, such as some small mountain streams of the southern French Prealps. Cross-sections were surveyed to determine the difference in elevation between the present active channel and remnants of previously active alluvial surfaces, notably those still visible on 1948 air photos.

Finally, flood records were analysed for those rivers where narrowing had been determined and which had sufficiently long hydrological records to test for possible decreases in flood magnitude or frequency during the period of active channel narrowing. The annual peak flow and the annual number of days for which the discharge is above the one-year recurrence-interval flood was plotted for three rivers – the Ubaye, the Drôme and the Rhine – for which available records begin during the 19th or early 20th century. The Rhine River did not narrow during the historical period because it was channelized in 1868–1870, but it has a gauging record back to 1809 at Basel and it is interesting to study its trend because the catchment underwent the same land-use changes as the Rhône. For the period 1900–1995, daily flood frequency records are compared for three distinct subperiods: 1900–1945, 1945–1970 and 1970–1995. The intermediate period is characterized by high rates of channel narrowing in the studied basins, whereas the two other periods show a relative stability or a minor decrease in channel width.

CONTEMPORARY CHRONOLOGY OF CHANNEL NARROWING

A general trend

In most of the studied basins, a general trend of channel narrowing can be established. A significant channel width decrease over the last 50 years can be observed not only on large rivers, but also on small mountain streams of the southern Prealps (Figure 3). Most of the streams underwent more rapid channel narrowing from 1950 to 1970 than from 1970 to 1990. It is notable that width changes were similar on the large piedmont rivers (Drôme, Eygues, Roubion, Ouvèze, Ardèche, Ain, Loire, Allier) and on the mountainous tributaries of the Prealps. Thus, a common pattern of channel narrowing is evident in space and time, regardless of position in the stream network. It is notable that the Drôme and the Roubion underwent strong narrowing not only between 1945 and 1970 but also from 1970 to 1990 (Figure 3).

The chronology of narrowing on 51 tributaries of the three Prealpine piedmont rivers also indicates an acceleration between 1950 and 1970. The mean rate of channel narrowing between 1948 and 1991–1996, calculated for the 51 tributaries, was 55 per cent. ANOVA performed to test the differences of this variable between the three basins reveals that mean rates were similar (p-values of F test are $>0{\cdot}05$ for each couple). Mean values of narrowing are 50, 58 and 62 per cent for the Drôme, the Eygues and the Roubion tributaries respectively.

On some basins, it was possible to characterize the pattern of active channel change over the last two centuries (Figure 4). A generalized trend toward channel narrowing was noted from the 19th century, with a strong acceleration during the 1950s and 1960s in most of the studied streams. On the Ubaye River, in the inner Alps, a 1895 photograph of its confluence with the Gimette torrent shows the valley floor completely unforested, whereas the forest corridor was well established by the air photo of 1948 (and still occupied this

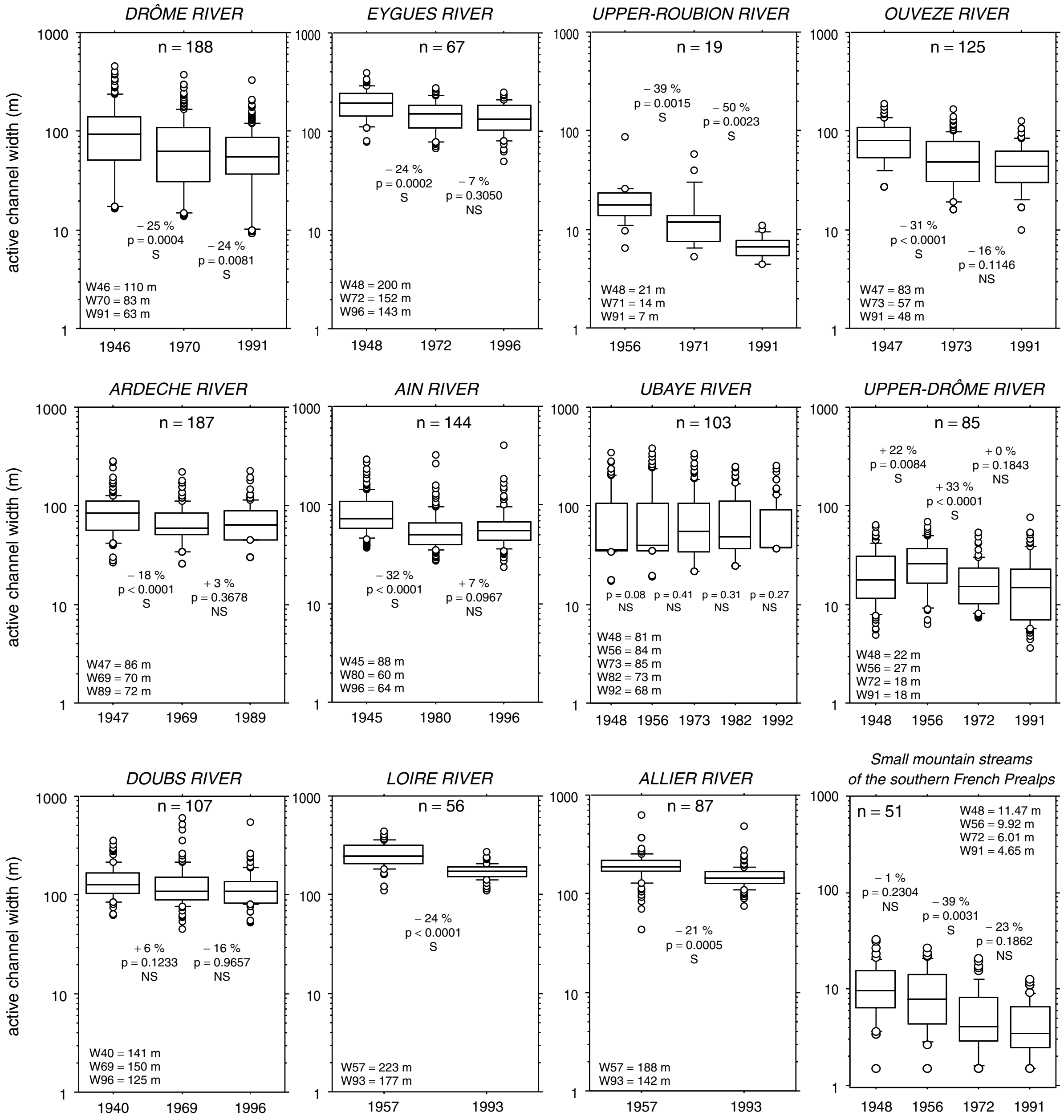

Figure 3. Active channel width changes that affected the studied rivers during the last 50 years (1950–2000); boxes represent inner and outer quartiles; vertical lines represent inner and outer tenths; open circles are extreme values; *n*, number of width measurements; *W*, mean values of active channel width for each date; values in per cent represents the rate of channel narrowing between dates; results of a non-parametric statistical test (Mann-Whitney *U*-test) are presented; S indicates significant differences of channel width between dates; NS, not significant

area in 1994; Figure 5). Dendrochronological analysis conducted in this forest showed that the trees were established between 1912 and 1935, with the average date of establishment being 1921. The old floodplain units in the study reaches of the Ubaye River were vegetated earlier than those of other rivers (Figure 6).

Dendrochronology on riparian forests established on former active channels indicates that forests because established mainly between 1950 and 1970, regardless of the size of the channel (Figure 6). Riparian forests

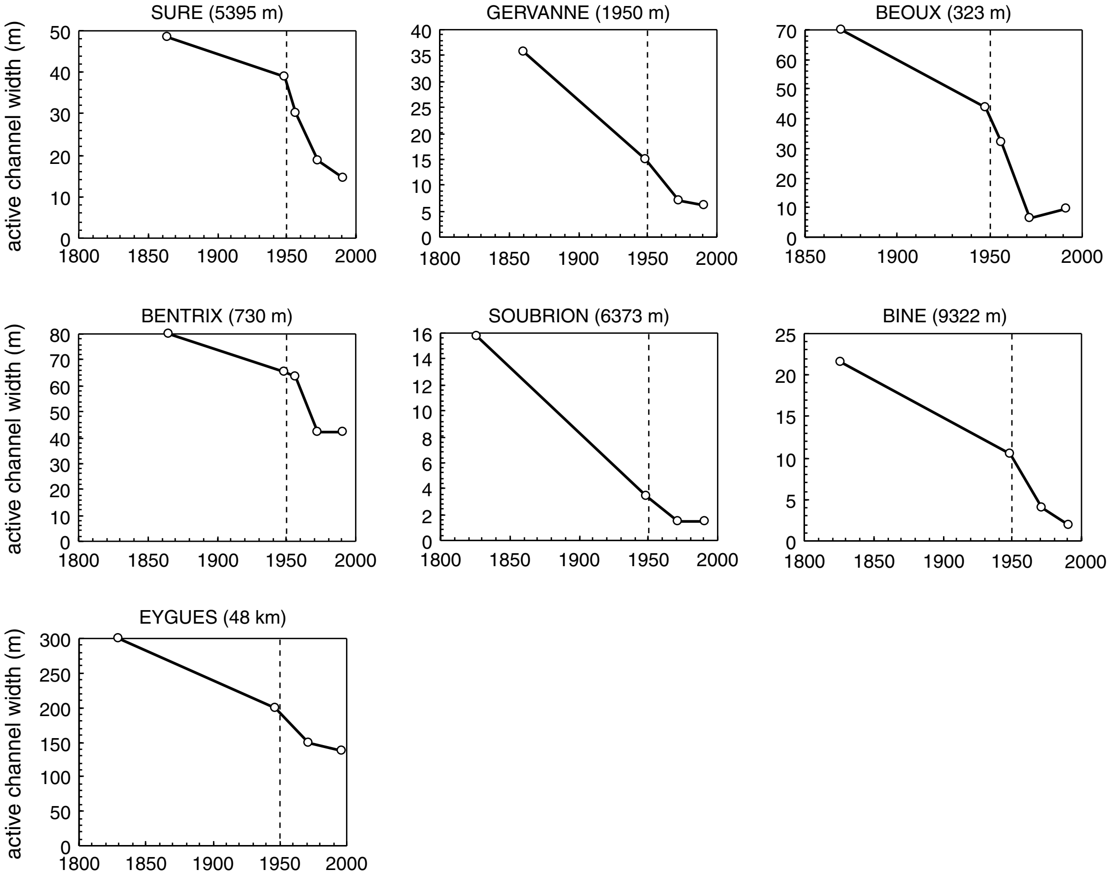

Figure 4. Pattern of active channel width evolution since the middle of the 19th century on one large gravel-bed river (Eygues River) and six small mountain streams of the southern Prealps; lengths of studied reaches are indicated in brackets

encroached at the same time on the channel of large piedmont rivers and on small mountain tributaries. These results indicate a remarkable temporal and spatial homogeneity in vegetation encroachment, with no evidence of lag time in responses of large and small rivers.

Some exceptions

The Giffre and Ubaye rivers, which are located in the inner Alps (an area with strong connection to hillslope sediment sources), did not undergo narrowing between 1950 and 1970 (respectively +2 per cent and +5 per cent). The Doubs River was also unusual in that it widened slightly between 1945 and 1970 (+6 per cent) (Figure 3). Its trend is all the more unusual in that the Doubs River is located in the piedmont zone of the Jura Mountains, within a basin similar to the Ain River.

Like the Roubion and the Drôme, the Ain River underwent a constant narrowing between 1947 and 1983, without inflection around 1970. Moreover, between 1980 and 1996, the Ain River widened by an average of 6 m year^{-1}, its surface area increasing from 435 ha to 457 ha over a reach of 35 km (see Figure 3). The case of the Soubrion stream (Figure 4) is also characterized by a more regular decreasing trend at the 20th century scale, without specific evolution between 1950 and 1970. By 1950, the Soubrion stream had already narrowed to 4 m wide. It did not experience accelerated vegetation encroachment after 1950, because narrowing between 1820 and 1950 was sufficient to stabilize all its previously active surfaces.

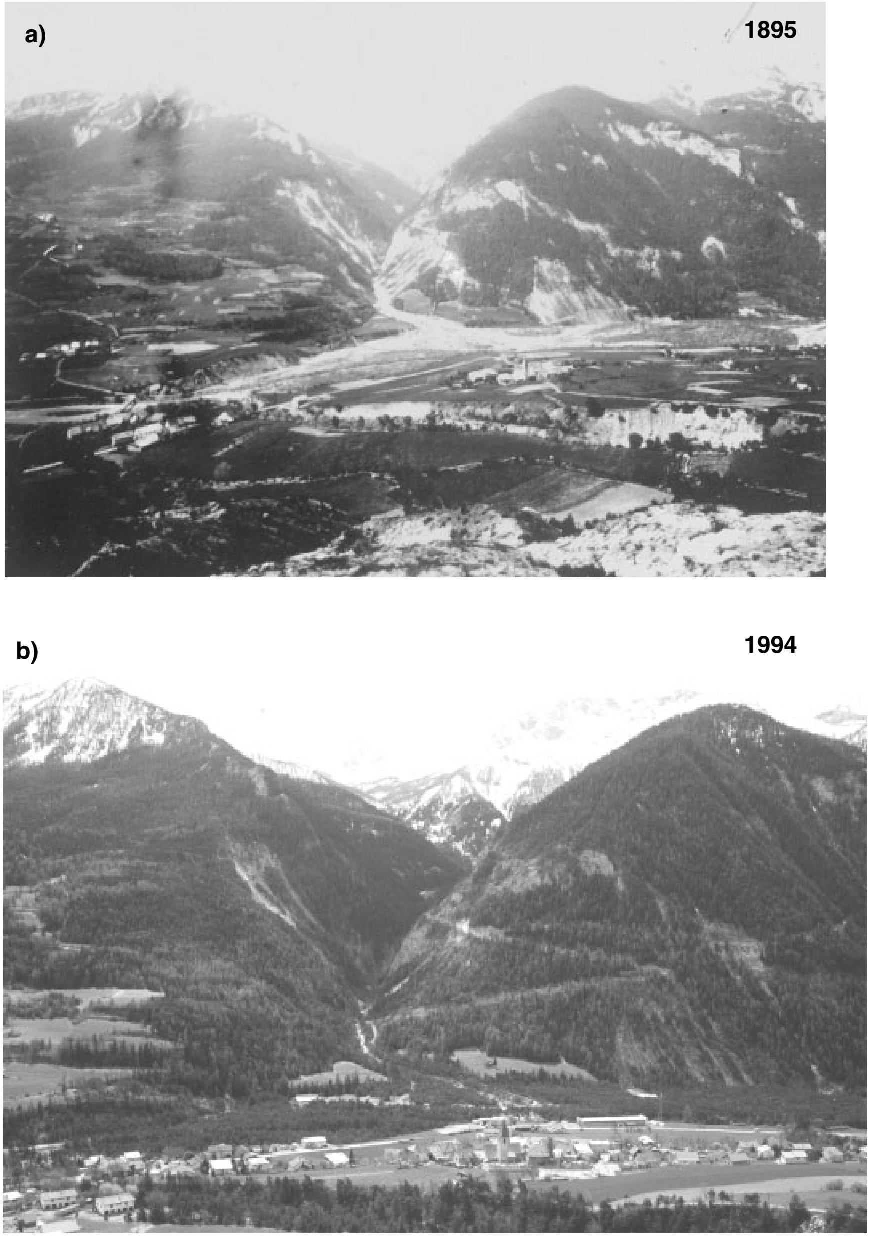

Figure 5. The Ubaye at its confluence with the Gimette torrent: (A) in 1895, the valley floor is occupied by discontinuous herbaceous plants and gravel bars; (B) in 1994, the valley floor is forested and the channel becomes narrower and deeper

REGIONAL CAUSES OF CHANNEL NARROWING

Channel narrowing: a complex process–response of the fluvial system

Results from this study illustrate the complexity of process–responses involved in the evolution of active channel width during the last 150 years. Channel narrowing occurred both on large rivers draining more than 1000 km^2 and small mountain streams with a high sensitivity to environmental change, and at about the same time. The long-term narrowing trend accelerated from 1950 onwards in rivers with channels wide enough for vegetation to establish. Historical information on channel widths from 1850 to 1950 is inadequate to quantify

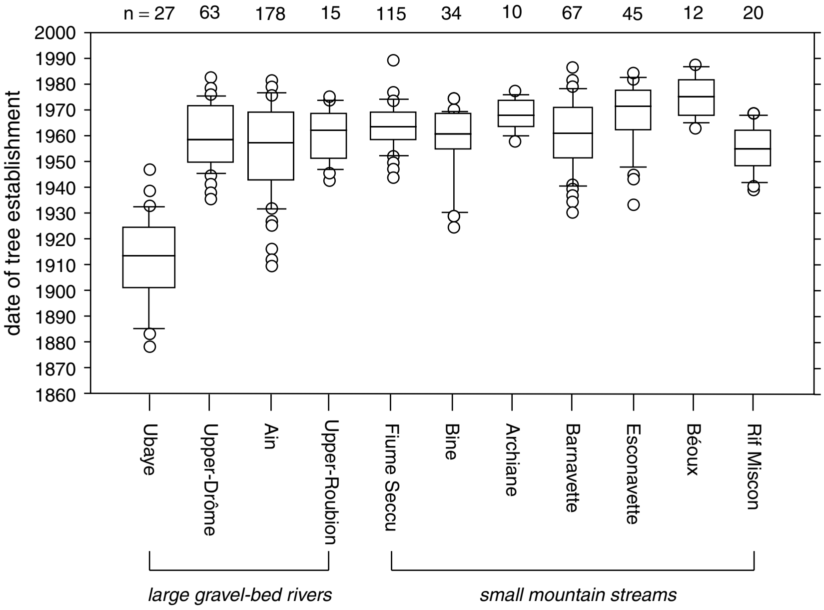

Figure 6. Distributions of the dates of tree establishment on first adjacent alluvial surfaces of active channels in different rivers based on dendrochronological measurements; boxes represent inner and outer quartiles; vertical lines represent inner and outer tenths; open circles are extreme values; *n*, number of sampled trees

variations in narrowing rates within this period. However, historical photographs of *c*. 1900 attest that most of the studied rivers maintained their braided pattern through this time, consistent with results of the historical analysis showing that post-1950 channel narrowing was a major fluvial change at the century scale.

Channel narrowing was commonly associated with pattern change from braiding to wandering, or from wandering to straight or meandering. On large piedmont rivers, as channel width decreased, sinuosity increased and braiding index decreased (Piégay, 1995; Landon, 1999). On small mountain streams most former active gravel bars stabilized, and channel morphology changed from wandering riffle–pool to straight confined patterns without well-developed open gravel bars.

Confronted with these fluvial changes, some authors have argued that the braided patterns could be considered as relict forms in most of the European mountains, in equilibrium with past climatic and erosive conditions, which resulted in high bedload supply and flood discharges (Bravard, 1991; Gautier, 1992; Miramont and Guilbert, 1997). Climatic changes following the end of the Little Ice Age (Le Roy Ladurie, 1983; Grove, 1988) and basin reafforestation induced by torrent control works and rural depopulation should have decreased bedload supply and peak flows, in turn progressively shrinking channels (see working hypothesis on Figure 1). This hypothesis can explain a long-term, gradual decrease in active channel width since the end of the 19th century but not the abrupt acceleration of the phenomenon after 1950. Moreover, in the southern Prealps, a similar intensity and pattern of narrowing occurred on the studied basins after 1950, whereas conditions of bedload supply decrease, notably torrent control works, differed among them.

1830–1950: channel narrowing associated with changes in bedload transport and discharge

Because of the long gap between the detailed maps and land-use descriptions of the Napoleonic cadastre (*c*. 1830) and the first aerial photographs (*c*. 1950), the analysis of narrowing is not easy for this period. Did narrowing occur slowly and consistently between 1830 and 1950 or more abruptly during a shorter period?

Torrent control works. On the Ubaye River, Piégay and Salvador (1997) previously showed from dendrochronological evidence that vegetation encroachment began abruptly around 1920. This major change has been strongly associated with torrent regulation realized from 1880 to 1900 15 km upstream. If average annual bedload movement is about 500 m, as observed on the Drôme basin where distances of transport are

Table II. Inventory of torrent control works carried on the Drôme, the Eygues and the Roubion basins between 1860 and 1978

	Drôme	Eygues	Roubion
Number of restoration perimeters*	53	23	1
Total area of restoration perimeters (ha)	27 428	6840	150
Turfing operations (t)†	406	41	0
Reafforested areas (ha)	13 217	2393	137
Number of wattlings and fascines‡	91590	1134	36
Number of check-dams	13 544	2387	0
Brush gully checks (km)§	599	158	0·2

* Area purchased by the French Forest Administration for the restoration of degraded lands.
† Use of grass to aid in revegetating a bare surface.
‡ Small dams made of twigs or flexible saplings woven between upright stakes.
§ Use of brush mulching or fascines in gullies to aid in revegetation.

determined after each flow event since 1997 on three mountain streams (Liébault *et al.*, 2001), the bedload retention upstream would affect the study reach of the Ubaye about 30 years after the works (consistent with the observations).

A comparison has been made of the chronology of torrent control works on a set of 51 mountain streams in the southern Prealps with the timing of active channel evolution downstream. The torrent control works from 1860 to 1920 were not uniformly distributed in space (Table II). Most were conducted in the Drôme basin, with very few structures (and little reafforestation) in the Eygues and the Roubion basins. The different density of torrent control works is a possible factor explaining the narrower widths of tributaries in the Drôme versus the Eygues basin in 1948 (mean active channel widths in 1948 are respectively, 10 and 14 m, significantly different at the p-level 0·03, Mann–Whitney U-test). Another factor is climate, with the Eygues basin being more Mediterranean, and thus more prone to high hillslope erosion rates due to the thinner vegetation cover and more intense rainfalls (cf. Wolman and Gerson, 1978; Descroix, 1994).

Results obtained on the Ubaye River and the southern Prealps suggest that the main period of fluvial adjustment to torrent control works was the first half of the 20th century. As such, they cannot explain post-1950 narrowing, even if the lag time for effects of mountain torrent control on piedmont rivers downstream is considered. Moreover, they cannot be the key factor explaining narrowing because shrinkage occurred on rivers with almost no torrent control works, such as most of the Eygues and Roubion tributaries.

Bedload supply decrease versus peak flow decrease: land-use change or climate change? The industrial revolution in the second half of the 19th century led to massive migration from rural areas to towns and cities. As a result, extensive ploughed lands were replaced by open shrub land and meadows in the first decades of the 20th century (Taillefumier and Piégay, in press). Comparison of historical land surveys in the southern Prealps indicates that area of shrub and meadow increased from 34 per cent in 1830 to 51 per cent in 1954, while arable lands declined during the same period from 32 to 6 per cent. These changes could have induced a progressive stabilization of hillslopes and a slow decrease of sediment supply to the stream network, leading to a progressive stabilization of gravel bars.

It is difficult to assess potential hydrological changes in the 19th and 20th centuries because few data exist. On the Ubaye River, gauging records back to 1904 reveal no change in annual peak flow that could explain post-1920 channel change (Figure 7a). On the Drôme, the gauging record at Luc-en-Diois back to 1907, augmented by historical records of large floods back to 1850, suggests that the 1850–1900 period had higher floods (Figure 7b). On the Rhine River, large floods occurred during the last part of the 19th century but the one-year recurrence-interval discharge series, at least since 1869, has been essentially stationary (Figure 7c).

The response of the Ubaye River to an estimated 1000-year flood in 1957 (Figure 7a) provides a test of the role of flood magnitude in determining channel width: the channel widened during the flood but narrowed within a few years after. The Upper Drôme River (Figure 3) illustrates a similar pattern of widening/narrowing

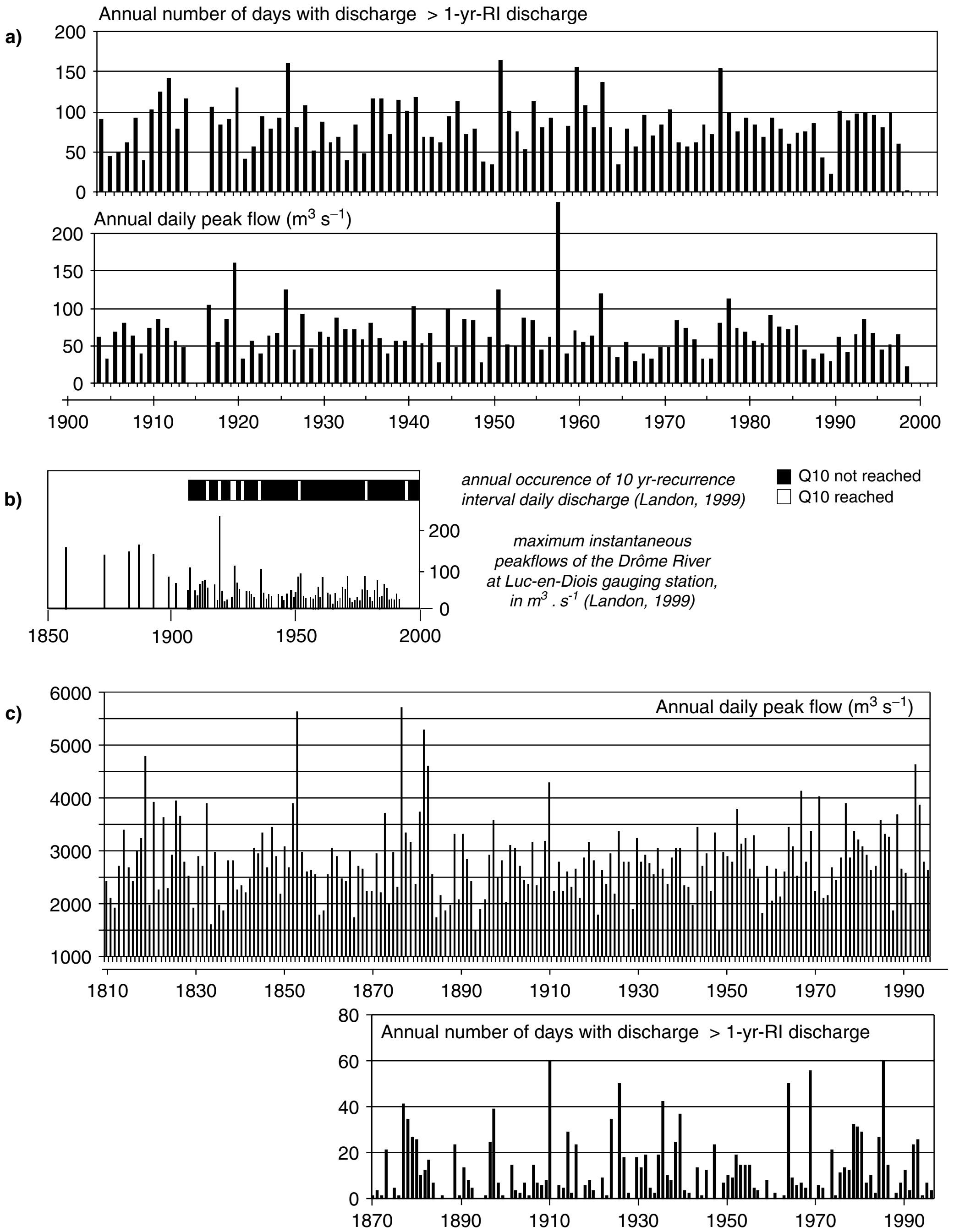

Figure 7. Hydrological fluctuations observed during the last two centuries: (a) the Ubaye record at Barcelonnette gauging station (drainage basin: 549 km^2, period of measurement: 1904–1999); (b) the Drôme record at Luc-en-Diois gauging station (194 km^2, 1907–2000); (c) the Rhin record at Basel gauging station (36 000 km^2, 1809–1999)

associated with a small sequence of moderate floods: four Q_{10} events occurred during 1953, resulting in a wider channel in 1956, but a few years later the channel returned to its pre-flood width. These observations suggest a sort of lateral periodic variation of the gravel-bed channel at time scales of one to ten years, which can be considered as simple fluctuations above and below a mean width (the dynamic equilibrium). These kinds of channel adjustments are independent of long-term changes such as those observed between 1830 and 1950.

All these numerous examples of channel adjustment following floods displayed recovery times of less than ten years. However, these observations of post-flood channel recovery occurred in a general context of decreased bedload supply, and were associated with chronologically isolated events, and thus would be less geomorphically effective than the sequence of large 19th century floods because the context was different.

The question of channel response to hydrological changes during the 1850–1950 period can be posed in terms of relative effectiveness of floods of different magnitude on fluvial geomorphology (Wolman and Gerson, 1978). Given that the large 19th century floods occurred in basins that were highly sensitive due to the degradation of the vegetation cover, their morphologic effectiveness may have been great enough to generate real modifications of the fluvial landscape. The morphological effects of these floods may have been enhanced by the fact that they occurred over a short period.

Floodplain land-use changes: replacement of ploughed lands by grazing. The Napoleonic land surveys of the first half of the 19th century clearly show that agricultural land use extended up to the edge of the active channel on most French rivers. Different floodplain areas studied on the Ouvèze River in 1830–1837 were mainly occupied by meadows or ploughed land (Figure 8a and b). Floodplain forest was very infrequent. There were stands of willows used by traditional farmers and artisans, precisely located on maps, but these

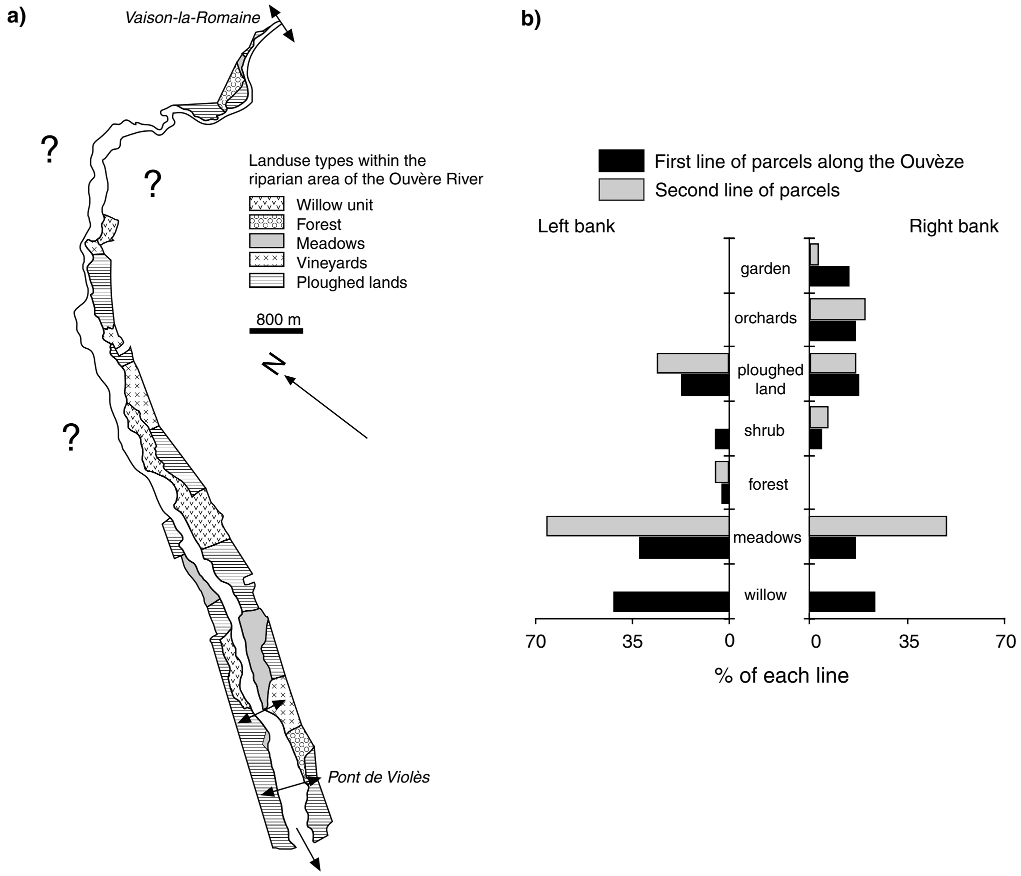

Figure 8. Riparian landscape of the Ouvèze River in the first half of the 19th century, based on the Napoleonic land survey (1830–1837); (a) Detailed map of riparian land-use types on a 15 km downstream reach; (b) proportion of land-use types observed on the two first lines of land parcels adjacent to the active channel

did not always form a buffer between ploughed area and the active channel. In the commune of Mollans-sur-Ouvèze, from 20 to 35 per cent of the parcels of land located on the border of the Ouvèze River were ploughed. A detailed diachronical mapping of floodplain land use on a small portion of the Ardèche River illustrates changes that affected the active channel boundary between 1833 and 1993 (Piégay, 1995). In this area, where the human pressure was greater than along the Ouvèze River, the Napoleonic land survey of 1833 showed that arable land occupied most of the floodplain surface and was its interface with the active channel. The 1933 land survey shows that the floodplain was dominated by shrub formations, which appear on aerial photographs as open grazed areas with dispersed shrubs.

Today, looking at the channels and their floodplain forests, it is difficult to imagine that the local communities used such area for cultivation, but statistics on historical population densities provide a glimpse of the former population pressure. In the communes of the Ardèche basin, population density was 60–100 inhabitants per km^2 in 1840–1850, compared with only 10–20 inhabitants per km^2 in 1990. Similar trends were observed in the Ouvèze basin and along the lower Ain (Piégay, 1995). Thus, the slow narrowing trend observed between 1830 and 1950 may also be caused by a change in floodplain resistance to areal erosion. Following rural depopulation, lower demand for corn, and changed agricultural practices, vegetation progressively encroached upon formerly ploughed, destabilized bar and floodplain surfaces.

In summary, for the period 1850–1950 it is interpreted that post-1900 channel narrowing occurred as a recovery process from an episode of widespread channel destabilization induced by floods in basins that were highly responsive to change following human disturbance. The recovery process was accelerated by floodplain and basin-scale land-use changes, and torrent control works which reduced sediment delivery and thus permitted vegetation establishment in channels.

1950–1970: channel narrowing associated with floodplain land-use changes and channel degradation

Three hypotheses are advanced in this study to explain post-1950 channel narrowing: (i) abandonment of intensive floodplain land uses such as grazing and riparian forest exploitation after 1950 in most French rivers; (ii) a phase of long-profile degradation in most of the studied rivers in the second half of the 20th century which induced the abandonment of active channels; and (iii) a possible hydrological trend toward decreased flood discharges after 1950. Each hypothesis is supported by evidence in studied rivers (Table III), as discussed below.

Land-use changes. Much of the historical evidence suggests that active channel narrowing since 1950 was due to abandonment of intensive floodplain land uses. This is illustrated by two rivers with very different

Table III. General synthesis on 1950–1970 channel narrowing occurrence and potential explaining factors

Rivers	Channel narrowing between 1950 and 1970	Flood discharge decrease after 1950	Forest development on floodplain after 1950	Degradation occurrence after 1950
Ain	■	■	■	□
Ardèche	■	□	■	■
Buëch	■	□	■	■
Drôme	■	■	■	■
Eygues	■	▒	■	■
Ouvèze	■	□	■	■
Roubion	■	▒	■	■
Southern Prealp tributaries	■	?	■	■
Doubs	□	□	□	■
Giffre	□	□	□	■
Upper-Drôme	□	■	■	□
Ubaye	□	□	□	■

Key: ■ well established occurrence ▒ uncertain occurrence □ absence ? unknown catchment hydrology and geomorphology, the Ardèche and Ain. The Ardèche drains the granitic Massif Central and flows through limestones in its piedmont reaches (Figure 2). The runoff is rainfall dominated, with a unit runoff of 0·012 m^3 s^{-1} km^{-2}. At Chauzon in the piedmont, the floodplain is now densely forested whereas 1933 land surveys and 1947 air photos show it was open meadow. The Ain River, which drains the higher elevation Jura mountains (mostly Jurassic limestones) (Figure 2), is dominated by snowmelt (or mixed rainfall–snowmelt), and has a unit runoff of 0·034 m^3 s^{-1} km^{-2}, three times greater than the Ardèche. Despite its different characteristics, the Ain underwent parallel changes in floodplain land use and evolution of active channel width. Along a 70-km study reach, forested area increased from 596 to 1219 ha, and the area of open active channel decreased by 40 per cent from 1947 to 1991.

A number of study rivers show a decrease in the rate of vegetation encroachment and reduction of active channel width after 1970, evidently reflecting the establishment of vegetation on most available surfaces by 1970 (Piégay, 1995). The Giffre and Ubaye Rivers, large rivers within the Alps, provide a variation on this theme. Their riparian forests were fully established by the 1940s, and cross-sectional geometry had already adjusted to forested boundary conditions. Thus, these rivers did not display significant narrowing after 1950.

The Doubs River provides an interesting contrast to the other rivers studied. The channel width of the Doubs was essentially stable from 1940 to 1996 (Figure 3). The explanation appears to be continuation of intense cattle grazing on the floodplain, which inhibited establishment of vegetation in the channel. Unlike other regions, where after the Second World War farmers generally shifted their agricultural production techniques and no longer used the riparian zone for grazing or cultivation, the farmers along the Doubs specialized in cattle production and continued to use the riparian zone for grazing.

Abandonment of agriculture in riparian zones is one of the major changes observed in rural areas in France after 1945 because of demographic shifts and increased agricultural specialization (to row crops and vineyards), instead of traditional polyculture-rearing over the entire landscape including the riparian zone. In the context of this change, the riparian forest could rapidly expand onto the floodplain and unvegetated bars. Moreover, the forested floodplains increased hydraulic roughness conditions, potentially reducing frequency of bed mobilization and thereby facilitating vegetation establishment on bars. On most rivers, this adjustment process stopped in the 1970s once a new equilibrium was attained between vegetation establishment and scour of seedlings, thereby maintaining an active channel. As trees were established on the floodplain, seedling stock increased, allowing for more rapid and dense colonization of the active channel.

Channel narrowing and channel degradation. Results from this study show that post-1950 channel narrowing was accompanied by degradation on several rivers (Table III), raising the question of the chronological relation of these two phenomena. In the large gravel-bed rivers studied, accelerated channel degradation is mainly explained by gravel mining, which was widespread in the 1970s, especially in the lower reaches. The mining-induced incision occurred after the vegetation encroachment in active channels, and cannot be viewed as a cause of channel narrowing. In the Ubaye and Giffre Rivers, which had already narrowed by 1950, between 1 and 3 m of channel degradation occurred in the 1970s, without any channel narrowing (Piégay and Peiry, 1997; Piégay and Salvador, 1997). These examples suggest that the disconnection of alluvial surfaces by degradation is not necessarily an important factor enhancing the development of vegetation on valley floors when the active channel has wide unvegetated gravel bars, because degradation due to mining affects not a small part of the active channel, but the whole width, comprising annually relocated low-flow channels and gravel bars.

In light of the link between in-channel vegetation encroachment and floodplain afforestation observed elsewhere (Millar, 2000), and taking into account that floodplain vegetation establishment is synchronous with in-channel vegetation encroachment on all the large gravel-bed rivers studied, it is concluded that in these systems, vegetation establishment is mainly the result of land-use change on the floodplain (including riparian areas), and that vegetation encroachment has accelerated channel degradation. With the reduction in bedload supply due to afforestation, the channels would probably have narrowed even if the floodplain land use had not changed, but at a slower rate, corresponding to the trend observed from 1850 to 1950.

It is also interesting to consider why narrowing continued after 1970 on the Roubion and the Drôme, but not on the Eygues or the Ouvèze rivers. A climatic explanation is proposed: the first two rivers are located in the northern part of the southern Prealps, with a less Mediterranean climate (and thus lower hillslope erosion rates) than the others. As a consequence, the relative decrease in bedload supply was greater, contributing more to vegetation establishment downstream. On the Eygues and Ouvèze rivers, the vegetation encroachment slowed down sooner, reaching an equilibrium with bedload transport, and maintaining a wide active channel. The Upper Drôme River illustrates this mechanism. This upstream reach has not narrowed, due to the persistence of high bedload inputs, reflected in a long-term aggradation of its long-profile (Figure 3). Thus, where bedload supply remain high, annual mobilization of the active channel bed can scour seedlings, and thereby prevent vegetation encroachment and channel narrowing.

Evidence of channel degradation is also observed on the small Prealpine tributaries, where confined narrow channels are incised in low terraces corresponding to the previous active channels abandoned between 1948 and 1971 (Liébault *et al.*, 1999). Detailed topographic surveys of several tributaries showed the mean difference in elevation between active channel and first adjacent alluvial surfaces to be 1·31 ± 0·60 m (based on 140 cross-sections). Dendrochronological dating of tree establishment on alluvial surfaces along five streams showed two main young alluvial surfaces on the modern valley floor (19th–20th century active floodplain) (Figure 9a). The lower surface corresponds to what were unvegetated gravel bars on the 1948 aerial photographs, the higher surface to the 19th century active channel as showed on detailed historical maps (Liébault *et al.*, 2001). Vegetation encroachment of these surfaces was not synchronous, with the higher surface mostly colonized between 1930 and 1950 and the lower one between 1950 and 1970 (Figure 9b).

The lag time between floodplain and active channel encroachment observed on mountain streams suggests that in-channel vegetation establishment cannot be considered as a simple adjustment to floodplain afforestation. Field evidence provides arguments to support this position: (i) the absence of surficial fine sediment deposits on low terraces (level L1 on Figure 9a) suggests that these levels were not constructed by vertical accretion following vegetation establishment in active channels, but were primarily generated by channel incision; (ii) the presence of pioneer species adapted to dry conditions (*Pinus sylvestris, Bruxus sempervirens, Juniperus communis, Salix eleagnos*) implies that the vegetation established on surfaces which became dry quickly following the disconnection process.

Based on these observations, channel narrowing on small mountain streams is considered to be a consequence of channel degradation related to the decrease in sediment supply following basin afforestation. The progressive stabilization of sediment sources induced a downstream-progressing degradation which disconnected margins of active channels. This is attested by a comparison of the timing of forest establishment on upstream and downstream sites in two tributaries of the Drôme basin (Figure 9c). These observations demonstrate that forest developed earlier on upstream reaches, which are closer to the stabilized sediment sources. The response of the vegetation to these channel changes may have been delayed by human controls (grazing and wood cutting) on vegetation development *c*. 1950 onwards, a fact that probably explains the timing homogeneity of in-channel vegetation expansion after 1950 between large and small rivers of the southern Prealps.

Schumm and Lichty (1963) demonstrated that active channel narrowing in the Cimarron River was associated with floodplain construction. This mechanism is also observed on large gravel-bed rivers of southeastern France where vegetation establishment on gravel bars is associated with fine sediment deposition. Observations made on mountain streams demonstrated that channel narrowing is not necessarily a result of floodplain construction, but rather a consequence of channel incision which leads to the formation of dry surfaces slowly encroached by pioneer species adapted to deep water tables.

Channel narrowing and hydrological change. Hydrological daily series for the last 100 years were analysed for basins with sufficiently long gauging records to compare the 1950–1970 hydrological period with others (Figure 10). Four basins were selected: the Ardèche, Drôme, Buëch and Doubs rivers.

Results for the Ardèche basin showed that flood discharge occurrence was higher during the period characterized by active channel narrowing. On the Buëch River, accelerated narrowing occurred during a period of frequent high flow events. On the Doubs River, the lack of active channel narrowing after 1950 cannot be related to a specific hydrological trend.

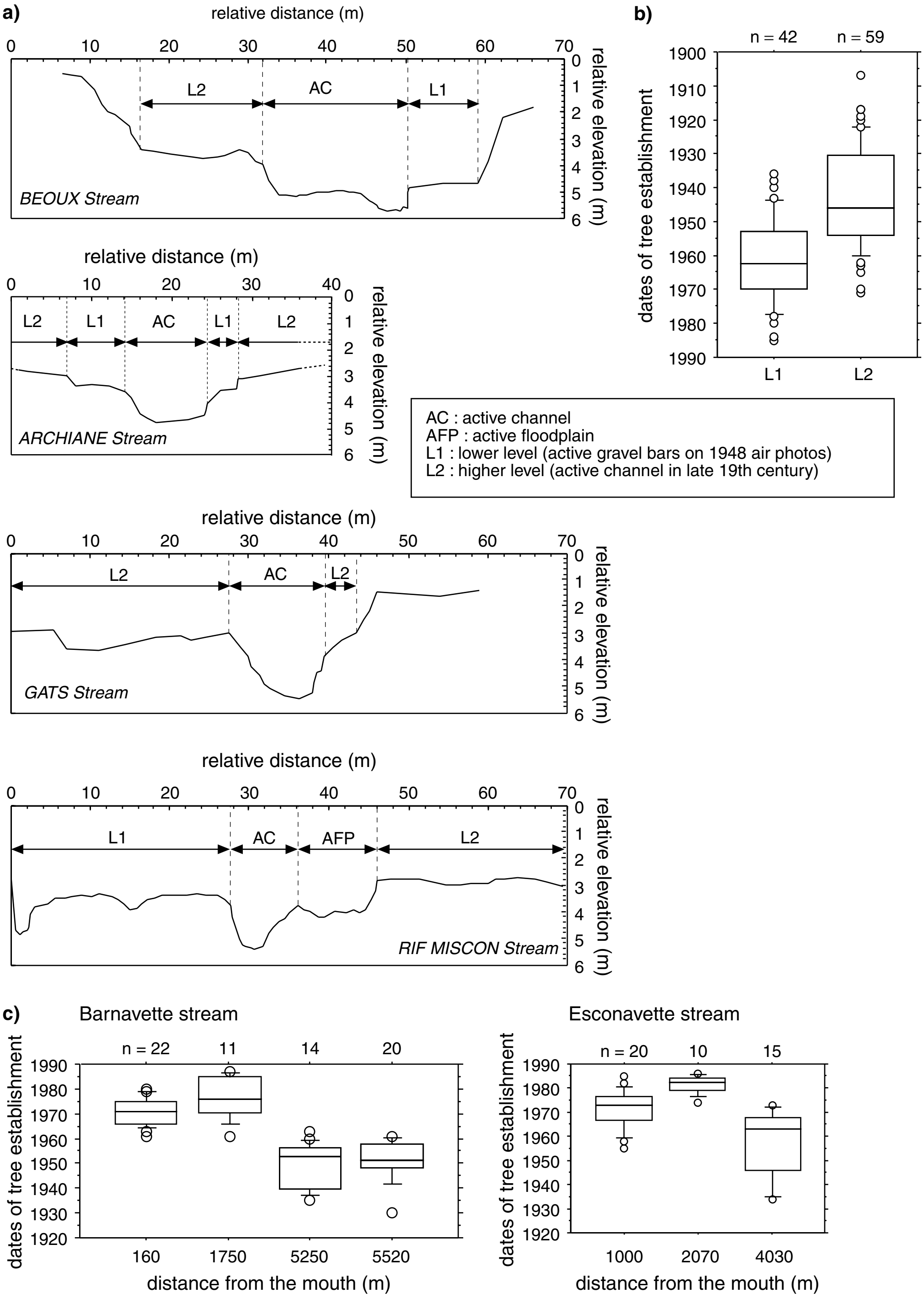

Figure 9. Cross-sectional geometry and forest establishment on several southern Prealps mountain streams. (a) Valley-floor cross-sections showing different alluvial levels; (b) distribution of the dates of tree establishment on the lower and higher levels (L1 and L2), based on dendrochronological dating sampled on the cross-sections presented in (a); (c) distribution of the dates of tree establishment on former active channels (level L1) in upstream and downstream reaches of two mountain streams of the Drôme basin (Esconavette and Barnavette streams), based on dendrochronological dating; boxes represent inner and outer quartiles; vertical lines represent inner and outer tenths; open circles are extreme values

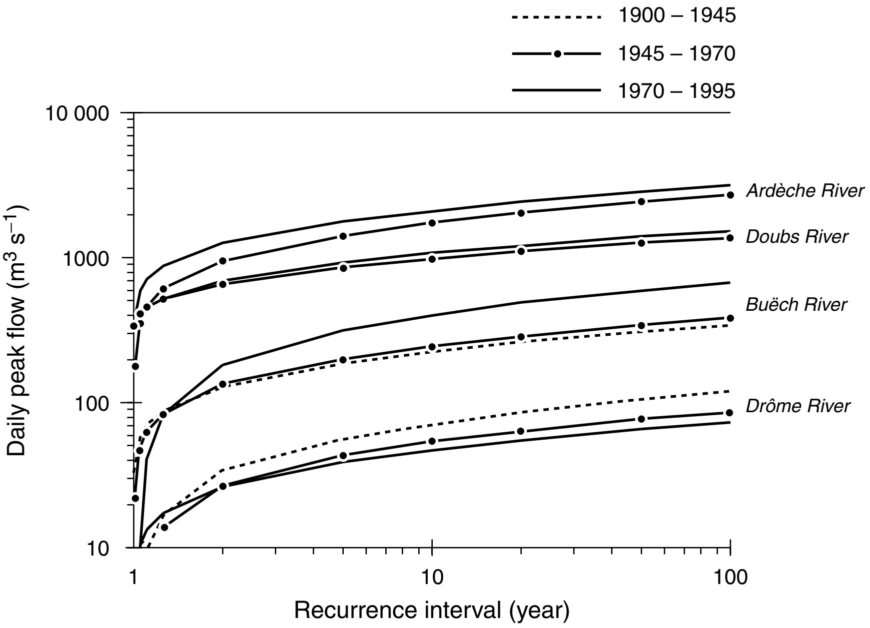

Figure 10. Comparison of daily flood-frequency curves between the period of accelerated channel narrowing (1945–1970) and previous and subsequent periods (1900–1945 and 1970–1995) on four large gravel-bed rivers: the Ardèche River at Sauze gauging station (2240 km^2, 1955–1997), the Buëch River at Serres (771 km^2, 1906–1990), the Drôme River at Luc-en-Diois (194 km^2, 1906–2000); the Doubs River at Besançon (4400 km^2, 1952–2000)

The Drôme River showed a different pattern, as the 1945–1970 period had smaller flood peaks than previous and subsequent periods. As recorded at Luc-en-Diois gauge since 1907, the 1945–1970 period was characterized by an absence of daily flow events exceeding the ten-year recurrence interval. This period coincides with the most extensive encroachment of vegetation in active channels in most of the studied tributaries, although vegetation encroachment continued afterwards despite higher peak flows.

Taken together, the hydrologic analyses show that channel narrowing was not restricted to periods of lower peak flows, so hydrological variations cannot provide a general explanation for channel narrowing, though perhaps they were a contributing factor on the Drôme. Moreover, the high rates of channel narrowing, to typically around 50 per cent of the former active channel width, seem too large to be explained by the relatively subtle hydrologic differences in the basins displaying a change. Hence, the magnitude of flood discharge variability is considered to explain only short-term fluctuations of the contact between active channel and riparian forests, as observed along the Ubaye River (Piégay and Salvador, 1997). The trend of channel narrowing after 1950 is more persistent and extensive. Some high floods occurred in several studied streams between 1940 and 1970, without modifying the trend toward channel width decrease. On the Roubion River, important floods occurred in 1960 and 1993, without inducing significant active channel width increase (Liébault and Piégay, 2001).

CONCLUSION

Channel narrowing has been observed in many different areas in the southeastern part of France over the past two centuries, including both piedmont and intramountain large gravel-bed rivers, as well as small mountain streams. Numerous channels have narrowed since the mid-19th century, with a marked acceleration from 1950 to 1970. Although some exceptions can be identified, on many of the studied rivers the narrowing was remarkably homogeneous in space and time. The synchronism of narrowing longitudinally along rivers, and among rivers regionally, is an important finding of this study, as is the chronology of forest establishment in valley floors, mostly during the 1950s and 1960s.

Two different periods are distinguished to facilitate causal interpretation. The 1850–1950 period (in which a gradual narrowing was observed) is difficult to interpret in terms of controlling factors. First, data are still missing to account for a possible timing complexity of channel narrowing. Although one example of rapid forest establishment around 1920 linked to torrent control works is documented (the Ubaye River), it is difficult to generalize and to determine strong causal relations between channel narrowing and climate or human controls. Long streamflow gauging records are rare, and among those that exist, some indicate a decrease in annual peak flows, but not in dominant discharges likely to control the channel width over the long term. Thus, the geomorphic effectiveness of a possible hydrological change is questionable, since many human disturbances (torrent control works, land-use changes) occurred at the same time and could have overwhelmed the effects of any changes.

Channel narrowing during the 1950–1970 period was more pronounced and was clearly related to human controls, such as floodplain land-use changes, mostly in alluvial sections, and hillslope afforestation associated with bedload transport decrease in mountain streams. It is suggested that vegetation encroachment in the active channel may have contributed to degradation during a period of overall bedload supply decrease because of hillslope stabilization. On some rivers, evidence suggests that the recent channel narrowing was not related to a period of smaller floods, a factor commonly cited as an important cause of channel width decrease. These lines of evidence are considered to indicate that the recent channel narrowing is primarily a human-induced phenomenon.

Human actions induced profound changes in sediment supply even at the scale of years to decades for reaches close to the sediment sources. Thus, even if the end of the Little Ice Age has had effects on river geomorphology, its effect is probably so slow as to be hidden by short-term human effects. This argues for caution in interpreting causes of channel changes, notably when linking long-term climatic effects and short-term human impacts.

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