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Contribution to assessment of the role of anthropic factors and bio-climatic controls in contemporary torrential activity in the southern Alps (Ubaye valley, France)

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1. Introduction

Changes in torrential activity have been studied by several authors who use active channel fluctuations as an indicator. These assessments aim to analyse the relations that exist between the morphology of rivers considered as fluvial systems (Schumm, 1977), and the sensitivity of their watersheds exposed to anthropic and natural controls (Bravard, 1991; Bravard and Peiry, 1993). Recent studies concerning a number of gravel-bed rivers (Gautier, 1992; Liébault et al., 1999; Landon and Piégay, 1999) and of piedmont torrents (Liébault et al., 2000; Liébault and Piégay, 2001; Liébault and Piégay, 2002) located in south-eastern France, indicate ubiquitous active channel narrowing during the 20th century. The study of floodplain forest evolution along the middle Ubaye river has also made it possible to identify the causes and chronology of the contemporary narrowing of this intra-mountainous gravel-bed river, showing a decrease of bedload supply consecutive to mountain reafforestation at the end of the 19th century (Piégay and Salvador, 1997).

Existing works have identified factors which control active channel morphology. These are (1) the sensitivity of sediment sources in watersheds, themselves conditioned by forest cover (Jorda, 1980; Liébault et al., 2000; Marston, 1994; Neboit, 1983; Vacca et al., 2000), (2) the type of bedload transport (fluvial and/or debris flow) (Flez and Lahousse, submitted; Kostaschuk et al., 1986; Marchi and Brochot, 2000), (3) the climatic context (Jorda, 1985; Miramont, 1998), (4) human controls which have an impact on sediment transport (Bravard and Peiry, 1993), (5) floodplain forest evolution (Piégay, 1995), (6) and main river incision as a result of bedload supply decrease and gravel mining (Bravard, 1994).

However, evaluation of the respective importance of fluvial bed adjustment causes is a major difficulty in this kind of approach (Landon and Piégay, 1999), because these factors are usually in strong interaction with one another and their effects tend to superimpose themselves from upstream to downstream in the fluvial system. A study of the parameters of active channel narrowing on mountain torrents located upstream of the system should make it possible to assess their respective roles. Two torrents, comparable from a natural point of view, have therefore been selected in the middle Ubaye river valley: the Riou Bourdoux and the Abéous. Between 1950 and 2000, the mean width of their active channels has diminished considerably. Whereas in the Riou Bourdou, this narrowing is generally accredited to reafforestation and torrent control works done by the state services as from 1866, in the Abéous watershed, this causal relationship cannot be referred to as the state service intervention, which only began in 1988. By comparing the contemporary changes in these two watersheds, in relation to channel narrowing, we intend to re-evaluate the role of anthropic and bio-climatic factors.

2. Similar geographical conditions, but a very different history

2.1. *The study site*

The Riou Bourdoux is located in the municipality of St. Pons, in the middle Ubaye valley (*Fig. 1*). Trending north–south, its large 2200 ha basin is the biggest one on the south facing slopes of the Ubaye valley. It is open in the geological fenster of Barcelonnette, and its upper slopes are cut in the Parpaillon Helminthoïd flysch nappe. The nappe lies on autochthonous black marls of the late Jurassic age (Callovian–Oxfordian), extremely sensitive to erosion processes (Meunier et al., 1995; Simonet et al., 1995). The black marls are frequently gullied into badlands, which, during storms, deliver a large volume of fine sediments to the torrent. The gradient in altitude between the highest point of the watershed and the confluence with the Ubaye river is about 1800 m, giving an average slope angle of 23% for a 7.5 km course. The slope gradient reaches 40% in the upper basin, it is of 17% in the channel and lowers to 6% on the alluvial fan.

From a geomorphological point of view, the Abéous is similar to the Riou Bourdoux. Located in the municipality of Revel (*Fig. 1*), its watershed, with an area of 1440 ha, is the second in size on the south facing slopes of the Ubaye valley. Above the black marls, the upper part of the watershed is formed of abrupt slopes cut in the allochtonous series of flysch and grey limestones of the Autapie nappe. The Abéous flows trending north–south, from 2811 m at the Montagnette to 1030 m at the confluence with the Ubaye river. The total gradient in altitude is around 1800 m for a 5.5 km course, giving an average slope angle of 32%. The slope gradient reaches 66% in the upper part of the watershed, 20% in the channel and lowers to 10% on the alluvial fan.

2.2. *The human impact on both basins is radically different*

2.2.1. *The Riou Bourdoux, symbol of mountain terrain restoration's success*

Even if the Riou Bourdoux is now considered as a reasonably tamed torrent by the Mountain Terrain Restoration department of the Alpes de Haute Provence (RTM), while remaining under close supervision

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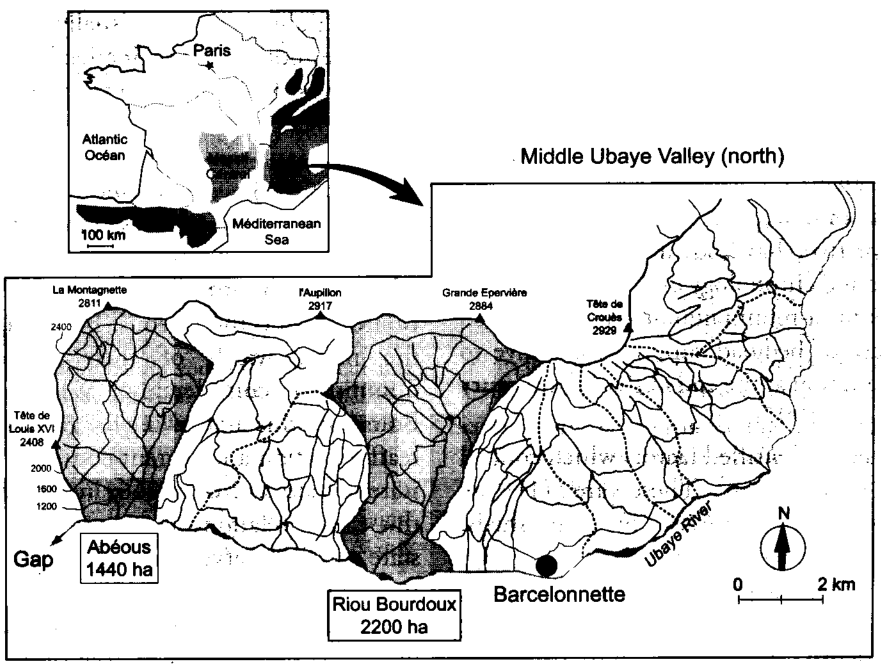


Fig. 1. The middle Ubaye valley and the studied basins (*Flez, Lahousse*).

(Delsigne et al., 2001), it was known as the "first torrent of France" at the end of the 19th century (Demontzey, 1894). At that time its debris flow floods were so frequent that they interfered with the development of Barcelonnette. As from 1866, the correction of this torrent was an emblematic challenge for the first defenders of the RTM work. At that time, torrentiality in the southern French Alps was considered as a historical phenomenon, with principally anthropic causes, resulting from overgrazing and deforestation. This traditional point of view to which Alexandre Surell's work contributed initial scientific support in 1841, is the origin of the gigantic RTM work undertaken since the middle of the 19th century by the national forest administration. The major part of the watershed was sold to the state by the municipality of St. Pons in 1864, and the works done between 1866 and 1914 aimed to make unprecedented global correction, by combining engineering and reafforestation. By 1871, 685 ha (31% of the watershed) of grazing land had been planted with grass. Between 1875 and 1892, the forest surface had risen to 1100 ha (50% of the watershed). In the meantime, the badlands in the Callovian–Oxfordian black marls were stabilised, by using faggot work made of live willow branches, as well as 1285 small stonework dams. By 1880 the drainage basin was under control, so the work in the channel could begin.

The aim was to fix the bed of the torrent by using a series of dams one upon another; upstream of a major dam. Downstream, to prevent undermining, a check dam and 40 stonework riffle dams to brace the bed down to 1330 m in altitude.

Upstream, in order to improve the alluvial deposit banking up of the major dam and to stabilise the banks by bringing the level of the bed up, 14 dams were built between 1889 and 1897. The target was reached, since the bed was raised by 33 m in the area where the main channels of the torrent meet and where a large lateral mass movement forced the torrent into a gorge. The hydro-geomorphologic functioning of the Riou Bourdoux has been radically transformed by man in order to maximise control over every parameter of its torrentiality; in the basin, where the sedimentary sources have been methodically run dry by using reafforestation of the slopes and extinction of the gullies in black marls; in the channel and on the alluvial fan where sediment transport and therefore long profile evolution have been subjected to permanent checking.

2.2.2. The Abéous: a great uncorrected torrent

Historical research testifies that at the end of the 19th century, the Abéous was just as active and as dangerous as any other large torrent of the Ubaye valley (Flez, 2000). During storms, it carried cobble and boulders, sometimes interrupting communication for several days. Just as the Riou Bourdoux, it hindered traffic in the valley and therefore interested the forest administration. The Abéous basin was included, in the same way as most torrents of the Ubaye valley, in the photographical survey of the years 1889–1895, which covered the Ubaye restoration project. The land included in this perimeter was submitted to the forest regime, which was extremely restrictive concerning agricultural activities.

Nevertheless, at the end of the 19th century, when the Ubaye valley municipalities were almost exclusively rural and mostly very poor, the loss of grazing income was difficult to handle. In these conditions, the state intervention in order to reafforest mountains implied interest conflicts. At Revel, historical investigations reveal that during the second half of the 19th century, the town council opposed constant resistance to the forest administration who was never able to intervene in the Abéous basin. Such an exception in the Ubaye valley can be explained by the fact that Revel depended exclusively on grazing income. Another explanation is that the threat represented by the torrent to circulation was removed in 1866 by the building of a stonework bridge on the RN 100 main road.

Excluded from the forest regime, the Abéous watershed did not benefit from reafforestation and correction works. Anthropic pressure was maintained, sheep grazed in the upper parts of the watershed, while cattle were led to the torrent's riparian forest. Agro-pastoral pressure in the valley progressively diminished in correlation with the demographic decline, which affected the Ubaye valley between 1831 (18,800 inhabitants) and 1930 (9800 inhabitants). Among the causes of this demographic drain can be considered not only torrent damage, but also expropriations by the forest administration for the purposes of reafforestation of the valley (Yankovitch, 1940).

Land use change accompanying the decline of rural agriculture mostly took place after World War II, to the benefit of a new mountain tourist oriented economy (Avocat, 1979). In the 1960s, new houses were built on the Abéous alluvial fan, in the proximity of the torrent. After a series of floods in the 1970s and

1980s, the riverside residents were alarmed and asked for the state services to take charge of their protection. Therefore, in 1988 almost 400 ha of the Abéous watershed were sold to the state so that the forest administration could undertake reafforestation and torrential correction. Two large dams were built in 1988 and 1990 and some 800,000 trees were planted during the 1990s.

3. The evolution of torrential activity similar for both torrents

3.1. Reafforestation and spontaneous forest development

In 1846, during a visit to Barcelonnette, Blanqui (1846) predicted that if nothing was done, France would be separated from Italy by a desert before the end of the 19th century. Indeed, at the time, the Abéous watershed was, like most of the south facing slopes of the Barcelonnette geological fenster, almost totally deforested. Despite the municipal forest management efforts which are testified by the large number of debates of Revel's town council, in 1890 the Abéous forest was in a state of shreds (*Fig. 2*). A few disseminated clumps of trees covered about 35 ha (2.5% of the watershed).

The situation was more or less the same in the Riou Bourdoux watershed, a few clumps of municipal forest remained, saved by the drastic grazing regulations imposed by the council during the years preceding the sale of the land to the state in 1864. The 240 ha of the alluvial fan were entirely free of vegetation. A century later, turfing and reafforestation done between 1866 and 1892 have produced results and the forest landscape now offered by the Riou Bourdou is quite different from what it was at the end of the 19th century. The state forest of the Riou Bourdou now covers a little more than 40% of the 2200 ha of the watershed. It is mostly artificial, but the upper parts, above 2000 m, have been spontaneously occupied by the most resistant species. The same situation prevails on the alluvial fan where the desert of mud and stone, which existed a century ago, has been replaced by a forest of *Pinus sylvestris*.

The existence of the Riou Bourdoux forest testifies to the efforts made by the forest administration, but are they the only explanatory factor of such a transformation in the landscape? The development of forest areas in the Abéous watershed supplies some of the answers.

Between 1890 and 1948, in the Abéous watershed, without a single tree having been planted, forest surface increased from 35 to 150 ha, representing a little more than 10% of the watershed surface (*Fig. 2*). In the year 2000, forest occupied some 350 ha, almost 25% of the watershed, not including the reafforestation undertaken since 1990. In a little more than a century, the forest surface in the Abéous watershed has spontaneously been multiplied tenfold, without any intervention from the forest administration, and in the absence of any reafforestation or protective measures. This natural afforestation is mainly due to an extension of the clumps of trees which existed in 1890. The present physiognomy of the Abéous forest is quite different to that of the Riou Bourdoux forest: it is proportionally half the size, it is considerably more divided up and its upper limit is under 1900 m whereas it reaches 2300 m in the Riou Bourdoux. Such an increase of the forest surface represents a radical change in the land use of both watersheds throughout the century, simultaneously we can observe a major active channel narrowing.

3.2. Active channel adjustment

Fluctuations of active channel width on the alluvial fans of the two torrents have been measured by diachronical analysis of aerial photographs taken by the National Geographical Institut (IGN) since 1948. Two types of processing were selected. The first consists in measuring the width of active channels every 100 m, on their entire length, on all the existing photographs. A narrowing index can be calculated by considering index 100 as being the mean width of active channels in 1948 (*Fig. 3b*). The measuring results of 8 years have been represented by a curve diagram (*Fig. 3a*), making it possible to compare easily the simultaneous evolution of the two torrents.

The second method analyses the details of active channel width evolution. A series of large-scale sketch-maps of a representative area of each torrent were drawn. A geometrical adjustment of the aerial photograph was done (*Fig. 4*). It is therefore possible to reconstitute the active channel narrowing stages for both torrents and compare the differences, especially concerning the impact of floods on active channel width.

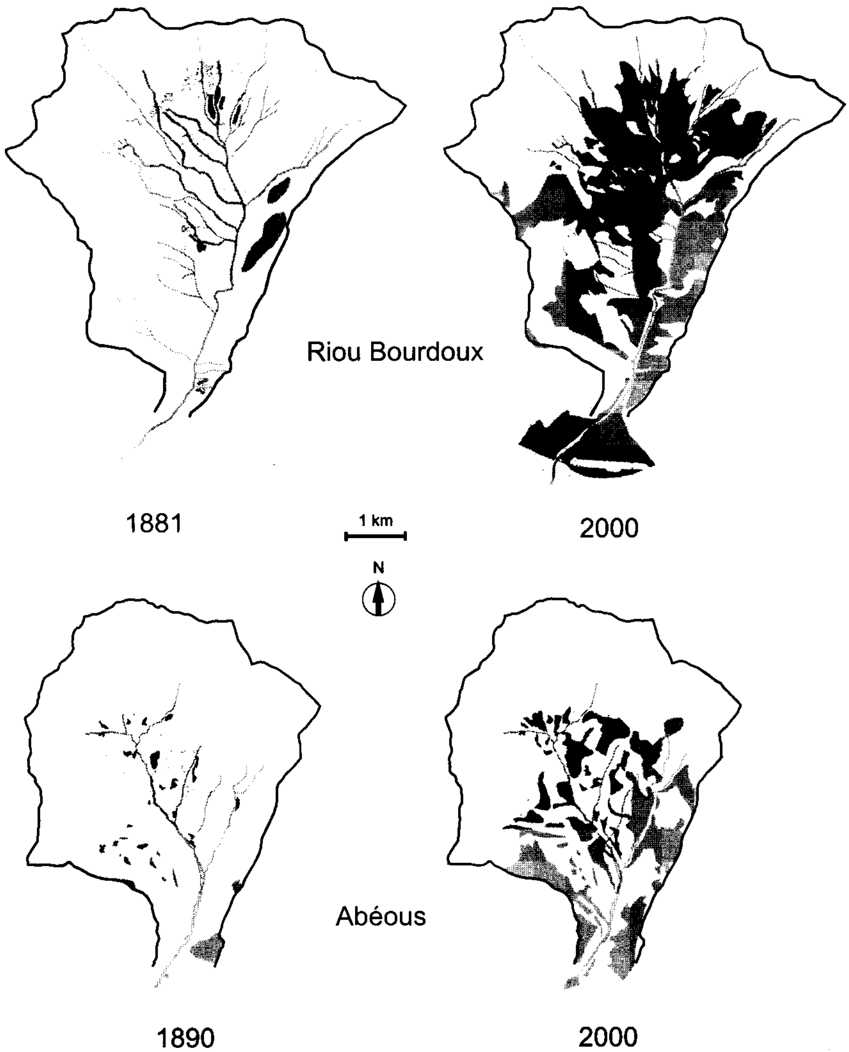
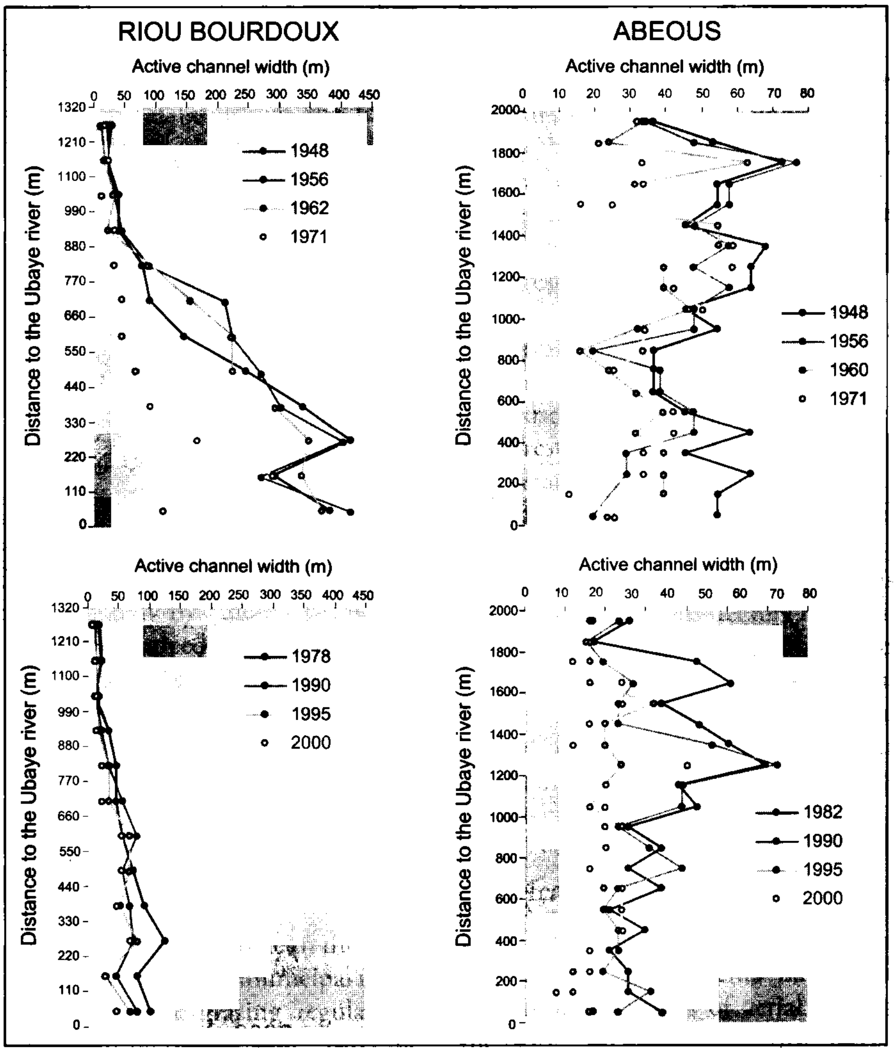


Fig. 2. Comparative forest development since the end of the 19th century in the two studied basins (*Flez, Lahousse*).

3.2.1. The rhythm of active channel narrowing is different for the two torrents

The 1948 situation (*Fig. 3a*) illustrates the morphometrical differences which exist between the two alluvial fans and the consequences on active channel morphology. The Riou Bourdoux has a large and regular alluvial fan, with a gentle slope (6%) which allows the 1300 m long active channel to spread out into a fan shape from upstream to downstream. Its width is less than 40 m at the apex of the alluvial fan, but it is over 400 m near the confluence with the Ubaye river. The Abéous alluvial fan has a steeper slope angle (10%) and a regular 2000 m long active channel with a maximum width under 75 m in 1948.

In the Riou Bourdoux, channel narrowing was not observed until the end of the 1960s. The 1956 photograph even shows a 9% enlargement of the active channel (*Fig. 3b*), certainly due to a flood in 1948. The 1962 situation corresponds to an adjustment after the 1948 crisis. In the 1960s and 1970s, on the contrary, channel narrowing is very fast, going from index 100 in 1962 to index 44 in 1971 and index 32 in 1978 (*Fig. 3a*). As from 1978 the rhythm slows down but narrowing continues regularly until reaching index 18 in 2000, with a maximum width inferior to 50 m. Between 1948 and 2000, the active channel narrowing in the Riou Bourdoux is over 80%. The major transformation in the active channel morphology begins as from 1962 and



a. Compared active channel width evolution

Year	1948	1956	1960	1962	1971	1978	1982	1990	1995	2000
Riou Bourdoux	100	109	n.c.	100	44	32	n.c.	25	23	18
Abéous	100	82	68	n.c.	66	n.c.	65	54	35	36.5

b. Channel narrowing index

Fig. 3. Active channel fluctuations of Riou Bourdoux and Abéous torrents since 1948 (*Flez, Lahousse*).

mostly takes place between 1971 and 1978. The active channel changes from a fan shape to a long and straight shape. There is no clear correlation between the changes in the active channel morphology and an absence of floods since over 10 debris flows having reached the alluvial fan were recorded between 1961 and 2000.

In the Abéous, between 1948 and 1971, channel narrowing is regular, but slower than in the Riou Bourdoux (*Figs. 3a and 3b*). This dynamic is perturbed by a major debris flow in 1973, whose consequences are visible until 1982. Afterwards, narrowing continues at a regular rhythm until 1990, before a brutal acceleration begins. The fast narrowing that takes place between 1990 and 1995 corresponds to the construction in 1988 and 1990 by the RTM of two dams at the apex of the alluvial fan. The effect is to stop bedload transport

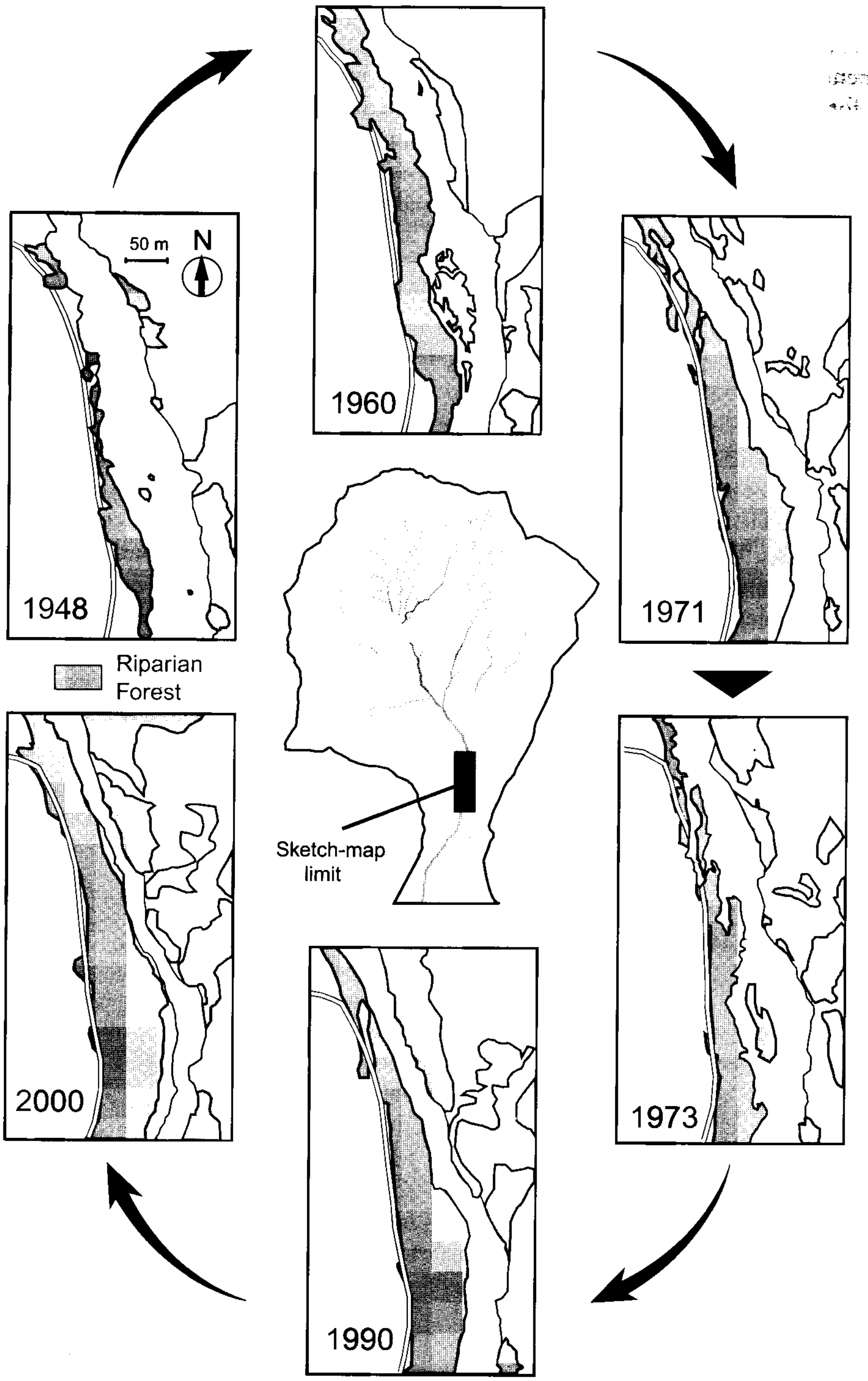


Fig. 4. Active channel narrowing in the Abéous between 1948 and 2000 (Flez, Lahousse).

upstream, which entails vertical erosion downstream, causing an entrenchment that can locally reach 6 m. This entrenchment is accompanied by fast narrowing, as most of the former active channel is perched in a terrace position, detached from the torrent's bed and already colonized by young *Pinus sylvestris* which benefit from the new xeric conditions. The slight enlargement measured between 1995 and 2000 (*Fig. 3b*) is probably due to bank erosion and a progressive return to post-entrenchment equilibrium.

The narrowing of the active channel in the Abéous is very unstable for each cross-profile, the areas abandoned by the active channel can be rapidly reactivated. The Abéous keeps a rectilinear channel over all the period but discrepancies to the general trend, i.e. local enlargements are frequent (*Fig. 3a*): they are nearly systematic during the 1948–1971 period and frequent between 1978 and 2000. They affect all cross-profiles, often exceeding 10 m, sometimes nearing 20 m. These discrepancies exist also in the Riou Bourdoux but they are far less frequent, representing half as many in proportion to the number of cross-profiles, as narrowing is more sudden and scarcely seems reversible. Finally, in the Abéous, active channel narrowing is about 65% between 1948 and 2000, whereas in the Riou Bourdoux it is over 80% (*Fig. 3b*).

3.2.2. Similar detail evolution of the active channels

Large-scale sketch-map analysis of representative reaches, mapped from aerial photographs, makes it possible to describe detailed evolution of active channel narrowing (*Fig. 4*). This latter favours the extension of the riparian forest, pioneer species such as *Salix* and *Pinus sylvestris* develop on gravel bars disconnected from the active surface, the riparian forest rapidly extends, both on gravel bars and from the banks.

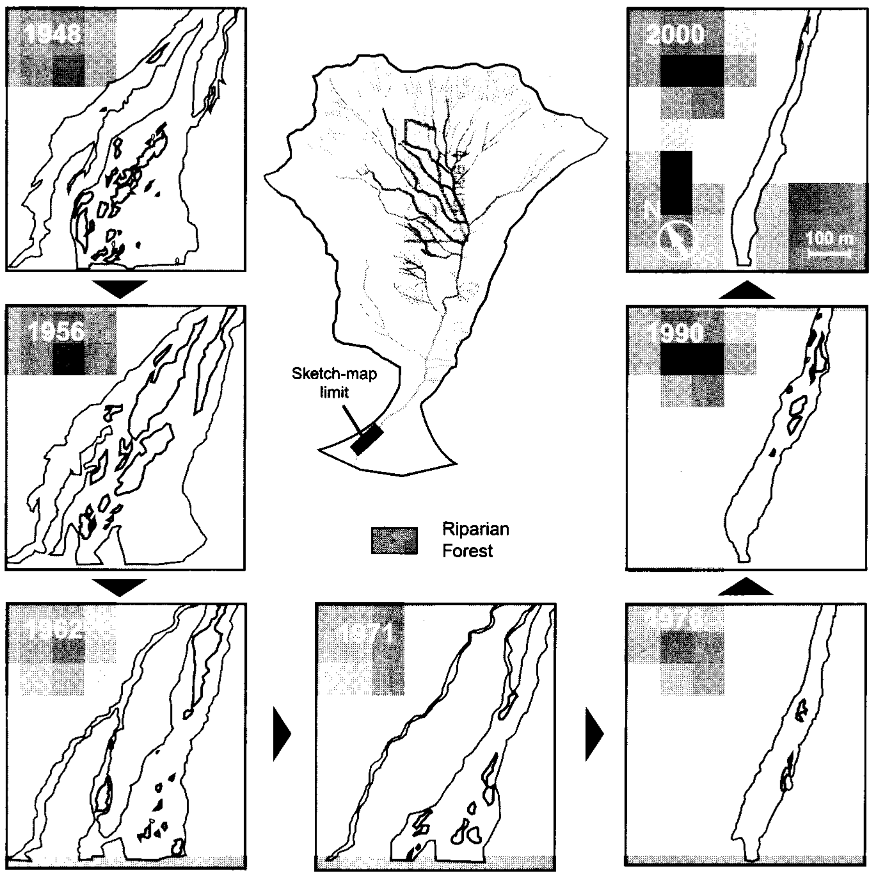


Fig. 5. Active channel narrowing in the Riou Bourdoux between 1948 and 2000 (*Flez, Lahousse*).

In the Abéous, vegetation which existed in 1948 has spread and occupies an island large enough to isolate a channel on the right bank. In 1971, this channel has disappeared under the forest. The 1973 situation illustrates the precariousness of riparian vegetation development in a torrent's active channel. In one flood, 25 years of forest extension were destroyed by the violence of the debris flow, emphasising the fact that small topographical differences between active and non-active channels are sufficient for vegetation to develop. Indeed, the debris flow used a channel which was active in 1948, is at the same altitude as areas which remained active afterwards. The vegetation benefited from a few year absence of floods to settle in this channel. The 1973 debris flow isolated the island existing in 1960 again (*Fig. 4*), and which corresponds to a metre high gravel bar. Wood sampling made in 2000 on the older trees located on this bar indicated ages around 45 years, corresponding to a settling of the trees in the 1950s. It seems therefore, that even if the narrowing phenomenon corresponds to a general trend, it is occasionally reversible during exceptional floods whose consequences are lasting since no return of the vegetation was observed before 1982, and it was not until 1995 that the riparian forest was fully regenerated.

In the Riou Bourdoux, by 1948 the vegetation had already settled on numerous isolated gravel bars. These had joined together and formed islands by 1956 (*Fig. 5*). Between 1956 and 1971, narrowing was very fast and all existing islands were coalescent by 1962. Thus the torrent's hold on the western side of its alluvial fan was greatly reduced. There was only a narrow channel left by 1971, over 60% of it having been taken over by riparian vegetation since 1948 (*Fig. 3b*). As from 1978, the fluvial style changed from a braided pattern to a wandering riffle-pool pattern, leaving only a long, straight and narrow active channel: 58 m mean width compared to 175 m in 1948. This development continued until 2000 with an important lateral development of the riparian forest, nevertheless, the narrowing rhythm is considerably slower than during the 1956–1978 period.

The two torrents have simultaneously reduced their hold on their alluvial fans, however the comparison shows some significant discrepancies. Narrowing rhythms are different. In the Riou Bourdoux, the major part of narrowing has taken place between 1962 and 1978, when two-thirds of the active channel were covered by vegetation encroachment. In the Abéous, narrowing was slower, less important during the 1948–2000 period, but it took place with a notable acceleration between 1948 and 1960. Besides, active channel evolution in the Riou Bourdoux did not seem to be affected by floods subsequent to the one of 1948, and few local enlargements are noted. On the other hand, the development of the Abéous is characterized by the importance of post-1973 flood enlargement, and also by the frequency of local enlargements linked to numerous floods which remain violent. This example testifies to the instability of this type of active channel limits, since one single event can durably disturb a long-term narrowing trend.

4. Discussion: active channel narrowing on mountain torrents, anthropic factors, natural controls

The debate about evaluating the respective parts played by climatic and anthropic parameters in the torrential crisis of modern times was at its height after the publication of a series of scientific studies during the 1970s and 1980s. Until then, the classical deforestation thesis, defended by contemporary authors (Arnaud, 1894), which legitimised RTM works (Demontzey, 1894; Surell, 1841), comforted *a posteriori* by historical research (Sclafert, 1959), considered torrentiality in the southern Alps, especially in the Ubaye valley where it was most spectacular, as a historical phenomenon, caused by overgrazing and deforestation. Nevertheless, in the 1920s, some authors discussed the extent and the age of deforestation, as well as its anthropic origin. They also criticised its morphodynamic consequences, arguing that torrentiality is part of a long-term climatic evolution (Fourchy, 1966; Lenoble, 1923). Later on, progress in palynology confirmed a forest draw back since the Middle Ages, but also showed that clearings had been made since the Bronze Age (Beaulieu (de), 1977; Wegmüller, 1977). Jorda's studies have shown that torrentiality is recurrent all along the Holocene. He established a correlation between post-glacial climatic changes and periods of torrential detritism. The stratigraphic study of alluvial fans has established a difference between early Holocene facies (*ante* 4700 BP) with a strictly climatic origin, whose "main Holocene fill-up" ("remblaiement Holocène principal") contains thick silt alluvial levels. And deposits attributed to Sub-boreal and Sub-Atlantic, mostly composed of debris flow heterometric sediment, of which modern times crisis would only be an episode, and that are linked to combined climatic and anthropic causes (Jorda, 1980, 1985, 1993). Jorda, as well as Douguedroit (1980), insist on the correspondence between the Little Ice Age crisis (approximately 1500–1850) (Grove, 1988), and the Modern Times morphodynamic crisis, arguing that repetitive floods of this period are well correlated to rainy summers and long snowy winters (Arnaud, 1894; Le Roy Ladurie, 1983), as well as glacier advancement (Coûteaux, 1982). Therefore, they conclude predominant climatic causes. Douguedroit discusses the extent of deforestation after the Middle Ages and argues that the southern Alps landscape was already in the 14th century very similar to the descriptions of 18th and 19th century authors (Blanqui, 1846; Ribbe (de), 1857). The situation seems not to have worsened during the Modern Times (Douguedroit, 1976). Increasing of torrential activity would consequently result from a more humid climate, and correlation between deforestation and torrentiality could therefore be largely criticised. The continuation of intense torrential activity during the 20th century, in spite of watershed reafforestation by the state services, tends to prove that density of vegetation has little influence on torrential dynamic (Collective, 1984).

The results of our study, which are corroborating some new data from recent studies, introduce new elements into this discussion. Concerning Modern Times torrential crisis, exclusive climatic explanation encounters several problems already pointed out at the time of these debates (Collective, 1984). Indeed, the definition of the Little Ice Age is founded on the advance of Alpine glaciers, but glacier fluctuations express a balance of mean climatic conditions over a long period. Torrents are, on the contrary, characterized by a spasmodic functioning, linked to local storms that contribute very little towards mean precipitations. Available data is insufficient at this time for it to be possible to assert objectively that the Little Ice Age is strongly correlated with an increase in the frequency and the intensity of storms. On the other hand, it has been proved that glacier advancement is caused by a combination of snowy springs, high summer rainfalls, and low temperatures (Coûteaux, 1982), these conditions being indeed favourable to triggering debris flows (Ballandras, 1998). However, to establish a purely climatic origin of modern torrentiality, it is necessary to prove a high increase of rain frequency and aggressiveness, compared to the period preceding the Little Ice Age. Otherwise, it seems reasonable to consider this crisis as the result of an anthropic lowering of rainfall efficiency threshold in torrent watersheds, combined with a cold and humid period. This diagnosis is supported by comparison between different Holocene torrential facies. On the scale of the southern French Alps, we can observe a clear increase of the detritic character of torrential deposits that seems to be synchronous with the rise of anthropic pressure on the slopes (Flez and Lahousse, submitted). Contrariwise to "main Holocene fill-up", whose silt levels testify to relative morphogenic stability, recent Holocene deposits are linked to anthropic action on the slopes (Jorda, 1993). Abéous stratigraphies dating from Iron Age and early Middle Ages indicate an intense but discontinuous detrital activity, testified by alternate heterometric deposits and silt levels, with periods of incision (Jorda, 1985), at the same time as the first clearings in the Ubaye valley during the Bronze Age are assessed (Wegmüller, 1977). When anthropic pressure reaches its maximum in the centuries following the Middle Ages, torrential deposits of the modern crisis show continuous and intense detrital activity, and contain no silt levels. (Ballandras, 1997; Flez and Lahousse, submitted; Jorda, 1985).

Concerning the influence of vegetation cover on torrential dynamic, several recent studies provide some answers. It is generally admitted that forest reduces annual runoff, and that conifers have a high rainfall interception capacity (Cosandey, 1995). It has been demonstrated that the combined action of climate and anthropic impacts in Mediterranean regions can have durable consequences on erosion efficiency of rain, soil quality and vegetation development capacity (Kosmas, 2000). Besides, land use is proved to have a major effect on runoff and erosion (Vacca et al., 2000), and efficiency of vegetation to increase the resistance of a surface to erosion is related to the density of cover (Brookes et al., 2000). These results correspond to those of other authors who have shown that land use change, and more specifically the reforestation of watersheds in south-eastern French piedmont, has induced an important active channel narrowing consecutive to the stabilisation of sediment sources (Liébault and Piégay, 2002). In these torrents, narrowing is accompanied by a lowering of fluvial competence that leads to channel incision and boulder pavement (Liébault and Piégay, 2001).

The Riou Bourdoux and especially the Abéous examples show that the relation between watershed reforestation and active channel narrowing can be extended to intra-Alpine mountainous torrents. Indeed, a systematic analysis of the parameters enumerated in the introduction makes it possible to conclude that vegetation cover has a predominant influence in the contemporary evolution of these two torrents.

We are henceforth able to discard controls linked to the Ubaye river. Neither the hydrological chronicle of the Ubaye river, available since 1904 (Piégay and Salvador, 1997), nor the mean annual rainfall in Barcelonnette (ONF data) indicate low discharge or low rainfall periods that could be correlated with active channel narrowing in the studied torrents. More generally, discharge variations on main rivers are too subtle to explain narrowing values superior to 50% in affluent torrents (Liébault and Piégay, 2002). As for long profile incision of the Ubaye river, especially linked to gravel mining and bedload supply decrease due to reafforestation in affluent watersheds, even if it is borne out along its middle course (Piégay and Salvador, 1997), it does not represent a valid explanation for channel narrowing on the studied torrents. Indeed, at the confluence with the Riou Bourdoux, comparison of the torrent's long profiles dating from 1879 and 1999 indicates a several metre channel aggradations due to torrent control works (Delsigne et al., 2001). Besides, the altitude of the confluence with the Abéous seems to have remained stable since the beginning of the 20th century, as it is located on a hard bedrock outcrop. This is confirmed by a topographic landmark installed by the General France Surveying service (NGF) on the bridge of Méolans, making it possible to adjust the long profile of the torrent measured in 2000 (Flez, 2000) on that of the Ubaye river dating back from 1908.

On the other hand, sediment supply reducing does not entail the same processes as those described in the southern Prealps (Liébault and Piégay, 2001). It seems that evacuation of bedload takes place during violent debris flows usually several years apart. To resume, we assess that watershed vegetation does play a major part in torrential dynamic and that its very advanced anthropic destruction, combined with the Little Ice Age climate, is a decisive explanatory factor for the lowering of rain efficiency threshold and the exclusively detrital facies of Modern Times crises.

A comparison between the Abéous and Riou Bourdoux torrents also indicates the variability of hydro-geomorphologic response intensity, according to lithologic and morphometric parameters, as well as intensity of anthropic impacts in each watershed. This aspect has already been put into evidence by several authors, at the time of a chronostratigraphic approach (Rosique, 1993), and for contemporary channel evolution (Liébault et al., 2002). The Riou Bourdoux is today in a state of higher morphogenic stability than the Abéous. This is partly due to the efficiency of the torrential correction system (Delsigne et al., 2001), but also to a much higher forest development, mostly due to artificial reafforestation. Nevertheless, the lithology of its watershed, especially the importance of very weathering sensitive black marl outcrops (Simonet et al., 1995) makes it more vulnerable to erosion than the Abéous. In other words, if active channel narrowing in the Abéous is the result of spontaneous reforestation consecutive to land use change during the second half of the 20th century, the superior morphogenic stability of the Riou Bourdoux is strongly linked to the efforts of the state services as from 1866 (*Fig. 6*).

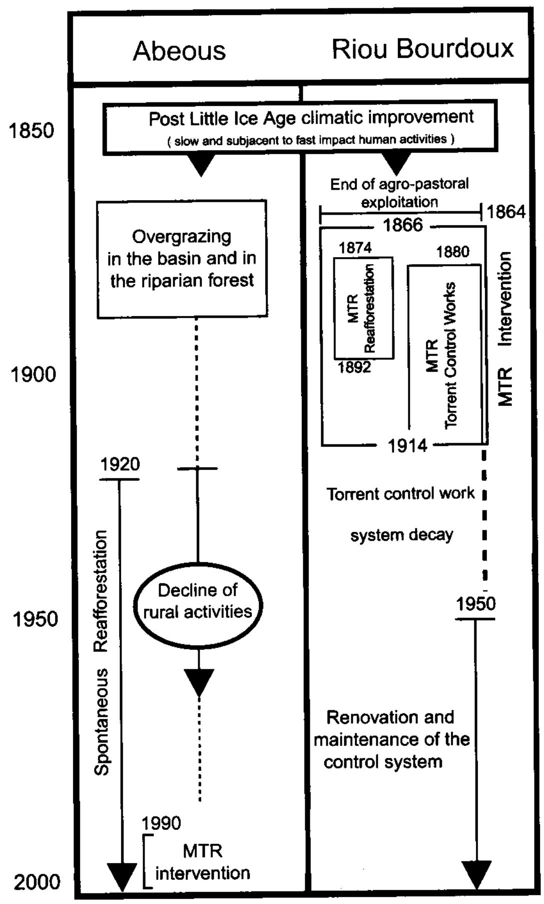


Fig. 6. Chronology of natural factors and of human controls in the basins of the Abeous and the Riou Bourdoux (Flez, Lahousse).

5. Conclusion

Active channel narrowing is an established fact in intra-mountainous and piedmont gravel-bed rivers, as well as in piedmont torrents of the southern Alps. This phenomenon remained to be proved in high Alpine mountain torrents. The example of the Riou Bourdoux and of the Abéous provides some answers on this subject. This study is also an opportunity to specify the role played by the various factors which condition this evolution. Anthropic factors appear to be of decisive importance in this case, on one hand in the most direct way with the torrent control and reafforestation work done by the forest department in many drainage watersheds; on the other hand in an indirect way as the decline of rural activities greatly favoured spontaneous vegetation development. The aim of this article is not of course to deny completely the climatic parameter, but it seems that the effects of the climatic change since the end of the Little Ice Age are considerably less perceptible on a short period, they are in any case subjacent to short term human effects.

Bibliography

Arnaud F., 1894. Documents et notices historiques sur la vallée de Barcelonnette. Laffitte reprints, Marseille.

Avocat C., 1979. Montagnes de Lumière (Briançonnais, Embrunnais, Queyras, Ubaye) : Essai sur l'évolution humaine et économique de la haute montagne intra-Alpine. Fayolle, Villeurbanne.

Ballandras S., 1997. Contribution à l'étude des bassins-versants torrentiels alpins. Stratigraphies, morphodynamique, paléoenviron- nements, de bassins–versants depuis 15 000 BP. Thèse de Géographie, Université de Savoie–C.I.S.M., Chambéry.

Ballandras S., 1998. Le « Remblaiement Historique » dans les bassins-versants torrentiels des Alpes françaises. Géomorphologie 1, 65–77.

Beaulieu (de) J.L., 1977. Contribution pollenanalytique à l'histoire tardiglaciaire et holocène de la végétation des Alpes méridionales françaises. Thèse de Sciences, Université d'Aix-Marseille III.

Blanqui M., 1846. Du déboisement des Montagnes. Renard, Paris.

Bravard J.P., 1991. La dynamique fluviale à l'épreuve des changements environnementaux : quels enseignements sont applicables à l'aménagement des rivières ? La Houille Blanche 7–8, 515–521.

Bravard J.P., 1994. L'incision des lits fluviaux : du phénomène morphodynamique naturel et réversible aux impacts irréversibles. Revue de Géographie de Lyon 69, 5–9.

Bravard J.P., Peiry, J.L., 1993. La disparition du tressage fluvial dans les Alpes Françaises sous l'effet de l'Aménagement des cours d'eau (XIX^e^ et XX^e^ siècles). Zeitschrift für Geomorphologie (Suppl. 88), 67–79.

Brookes C.J., Hooke J.M., Man, J., 2000. Modelling vegetation interactions with channel flow in river valleys of the Mediterranean region. Catena 40, 93–118.

Collective, 1984. La mobilité des paysages méditerranéens. Revue de Géographie Des Pyrénées et du Sud-Ouest, Travaux II, hommage à P. Birot.

Cosandey C., 1995. La forêt réduit-elle l'écoulement annuel ? Annales de Géographie, 581–582, 7–25.

Coûteaux M., 1982. Caractérisation pollenanalytique en Oisans des milieux forestiers et des milieux supra-forestiers dans l'actuel et dans le passé. In: Actes du Colloque « La limite supérieure de la forêt et sa valeur de seuil ». Terra Nostra, Perpignan, pp. 139–159.

Delsigne F., Lahousse P., Flez C., Guiter G., 2001. Le Riou Bourdoux (Alpes-de-Haute-Provence, France): un « monstre » sous haute surveillance. Revue. Forestière Française 5, 527–541.

Demontzey P., 1894. L'extinction des torrents en France par le reboisement. Imprimerie Nationale, Paris.

Douguedroit A., 1976. Les paysages forestiers de Haute-Provence et des Alpes-Maritimes. Géographie. Écologie. Histoire. Thèse, Édisud, Aix-en-Provence.

Douguedroit A., 1980. Les périmètres de reboisement dans les Alpes du Sud. Revue Forestière Française, n° spécial « Sociétés et forêts », 37–46.

Flez C., 2000. Le torrent de l'Abéous, facteurs bioclimatiques et anthropiques de la torrentialité holocène. Mémoire DEA de Géographie, Université des Sciences et Technologies de Lille.

Flez C., Lahousse P., submitted. Exemple of Holocène alpine torrent response to environmental change: contribution to assessment of forcing factors. Submitted to Quaternaire.

Fourchy P., 1966. Déboisement et reboisement. Les débuts de la lutte contre l'érosion au XIX^e^ siècle dans les Alpes Françaises. Revue Forestière Française 4, 467–487.

Gautier E., 1992. Recherches sur la morphologie et la dynamique fluviale dans le bassin du Buëch (Alpes du sud). Thèse de Géographie, Université Paris X-Nanterre.

Grove J.M., 1988. The Little Ice Age. Methuen, London.

Jorda M., 1980. Morphogenèse et évolution des paysages dans les Alpes-de-Haute-Provence depuis le Tardiglaciaire. Facteurs naturels et facteurs anthropiques. Bulletin de l'Association de Géographes Français 472, 295–304.

Jorda M., 1985. La torrentialité holocène des Alpes françaises du Sud. Facteurs anthropiques et paramètres naturels de son évolution. Cahiers Ligures de Préhistoire et de Protohistoire 2, 49–70.

Jorda M., 1993. Histoire des paléoenvironnements Tardi- et Postglaciaires sud-alpins de moyenne altitude. Essai de reconstitution cinématique. Géomorphologie et Aménagement de la Montagne n° spécial « Hommage à P. Gabert », 99–111.

Kosmas C., 2000. The effect of land parameters on vegetation performance and degree of erosion under Mediterranean conditions. Catena 40, 3–17.

Kostachuk R.A., Mcdonald G.M., Putnam P.E., 1986. Depositional process and alluvial fan-drainage basin morphometric relationships near Banff, Alberta, Canada. Earth Surface processes and Landforms 11, 471–484.

Landon N., Piégay H., 1999. Mise en évidence de l'ajustement d'un lit fluvial à partir de documents d'archives : le cas de haute Drôme. Revue de Géographie Alpine 3, 67–86.

Lenoble F., 1923. La légende du reboisement des Alpes. Revue de Géographie Alpine 14, 208–213.

Le Roy Ladurie E., 1983. Histoire du Climat Depuis l'An Mil, Flammarion, Paris.

Liébault F., Clément P., Piégay H., Landon N., 1999. Assessment of Bedload Delivery from Tributaries: the Drôme River Case, France. Arctic, Antarctic, and Alpine Research 31, 108–117.

Liébault F., Piégay H., Taillefumier F., 2000. Réponses géomorphologiques du Haut-Roubion (Drôme) à la reconquête végétale contemporaine de son bassin versant. Forêt Méditerranéenne 21, 177–181.

Liébault F., Piéga, H., 2001. Assessment of channel changes due to long-term bedload supply decrease, Roubion River, France. Geomorphology 36, 167–186.

Liébault F., Piégay H., 2002. Causes of 20th century channel narrowing in mountain and piedmont rivers of Southeastern France. Earth Surface Processes and Landform 27, 425–444.

Liébault F., Clément P., Piégay P., Rogers C.F., Kondolf G.M., Landon N., 2002. Contemporary channel changes in the Eygues basin, southern French Prealps: the relationship of subbasin variability to watershed characteristics. Geomorphology 45, 53–66.

Marchi L., Brochot S., 2000. Les cônes de déjection torrentiels dans les Alpes françaises. Morphométrie et processus de transport solide torrentiel. Revue de Géographie Alpine 3, 24–38.

Marston R.A., 1994. River entrenchment in small mountain valleys of the western USA: influence of beaver, grazing, and clear cut logging. Revue de Géographie de Lyon 1, 11–15.

Meunier M., Mathys N., Cambon J.P., 1995. Panorama synthétique des mesures d'érosion effectuées sur trois bassins du site expérimental de Draix. Compte-rendu de recherches nº 3 BVRE de Draix, Cemagref, Grenoble.

Miramont C., 1998. Morphogénèse, activité érosive et détritisme alluvial holocènes dans le bassin de la Moyenne Durance (Alpes françaises du sud). Thèse de Géographie, Université d'Aix-Marseille I.

Neboit,R., 1983. L'homme et l'érosion. Publication de la Faculté des Lettres et Sciences Humaines de l'Université de Clermont-Ferrand II, Clermont-Ferrand.

Piégay H., 1995. Dynamique et gestion de la ripisylve de cinq cours d'eau à charge grossière du bassin du Rhône (l'Ain, l'Ardèche, le Giffre, l'Ouvèze et l'Ubaye) XIXe et XXe siècles. Thèse de Géographie et d'Aménagement, Université de Paris-IV Sorbonne.

Piégay H., Salvador P.G., 1997. Contemporary floodplain forest evolution along the middle Ubaye River, Southern Alps, France. Global Ecology and Biogeography Letters 6, 397–406.

Ribbe (de) C., 1857. La Provence au point de vue des bois, des torrents et des inondations avant et après 1789. Guillaumin et Cie, Paris.

Rosique T., 1993. Détritisme torrentiel et activité érosive post-würmiens dans les Alpes méridionales Françaises : l'exemple de la région de Gap (Hautes-Alpes). Travaux U.R.A. 903 du CNRS 22, 53–61.

Schumm S.A., 1977. The Fluvial System. Wiley, New York.

Sclafert T., 1959. Cultures en Haute-Provence, déboisement et pâturage au Moyen Âge. Sevpen, Paris.

Simonet J.P., Richy P., Parron C., 1995. Contribution à l'étude des mécanismes et bilan de l'érosion chimique des « Terres Noires » du bassin de la Durance. Exemple des BVRE de Draix. Compte-rendu de recherches nº 3 BVRE de Draix, Cemagref, Grenoble.

Surell A., 1841. Étude sur les torrents des Hautes-Alpes. Dunod, Paris.

Vacca A., Loddo S., Ollesch G., Puddu R., Serra G., Tomasi D., Aru A., 2000. Measurement of runoff and soil erosion in three areas under different land use in Sardinia (Italy). Catena 40, 69–92.

Wegmüller S., 1977. Pollenanalytische untersuchungen zur spät—und post glazialen Vegetationsgeschichte der Französichen Alpen. Thèse inédite.

Yankovitch T., 1940. Le reboisement et la correction des torrents dans le département des Basses-Alpes. Ste-Blaize, Paris.