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Impact of Gravel-Mining on Stream Channel and Coastal Sediment Supply: Example of the Calvi Bay in Corsica (France)

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ABSTRACT

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Beach erosion during the last three decades in Calvi Bay, Corsica, is described and linked to a reduction of gravel and sand delivery from the Figarella and Fiume Seccu coastal streams. Recent assessment of bedload transport during a 1 in 2 year flood and stream bed changes evaluated from aerial photographs and field measurements (cross-sections, long profiles, sediment size analysis) show these streams deliver less and less sediment to the beach, thereby explaining its erosion.

Two main causes explain this trend: (1) in-channel gravel-mining has been operated on these streams since the 1970's and (2) significant land-use changes have taken place in their watershed since the end of the 19th century. The gravel pits trap sediments and induce adjustments in channel geometry. An alder forest that colonized the gravel pit on the Fiume Seccu traps most of the sand delivered by the watershed and represents a major flood risk because vegetation encroachment has increased hydraulic roughness. The excavation in the Figarella measures 600 000 m^3, corresponding to a channel degradation of 3 m. Channel degradation and armoring are also observed upstream and downstream of the excavation due to progressive and regressive erosion as a result of bedload transport disruption and downstream winnowing. The winnowing process has been very effective because bed material is heterogeneous. Field measurements demonstrate that less than 50% of the beach sediment deficit results directly from mining. Beach erosion is also linked to decreases in sediment delivery from the watersheds. Channel patterns have simplified even in the reaches which are not affected by mining. Braided channels have been replaced by single-bed channels and most of the channels observed in aerial photographs from the 1950's are now vegetated. Late 19th c. agricultural decline has led to land-use changes, croplands and pasture being replaced by spontaneous undergrowth and woods, reducing erosion and run-off.

Beach erosion, due initially to watershed land-use and channel changes on coastal streams occuring since the late 19th century, and worstened by gravel-mining, is far from under control. As gravel pits will continue to trap sediments for several decades, decision-makers should favor natural or artificial solutions to increasing sediment delivery if they want to maintain the beach, essential to the local tourist industry.

ADDITIONAL INDEX WORDS: *Beach degradation, gravel-mining, channel degradation, bed armoring, downstream winnowing, land-use changes, mediterranean streams.*

INTRODUCTION

In France, the number of gravel mining sites in active river channels increased dramatically during the 1960's and 1970's (BRAVARD, 1991; DAMBRE, 1996). Subject to limited and ineffective regulatory control, this form of resource exploitation produced extremely serious environmental impacts (TAGLIAVINI, 1978; LARINIER, 1980; KONDOLF, 1994 and 1997). Gravel mining in gravel-bed rivers, highly sensitive to any change in gradient, led to generalized progressive and regressive erosion that has lowered long profiles by as much as 10 m on certain rivers draining the western Alps (PEAUDECERF, 1975; PEIRY, 1987; PEIRY *et al.,* 1994). These geomorphic adjustments also destabilized works. For example, several kilometers of dikes have been damaged on the Drôme river (LANDON *et al.,* 1999). The cost of repairing these works and building weirs to stop degradation is far too great for the finances of local communities. Though most developed countries (KONDOLF, 1997) including France (BOUTTIER *et al.,* 1991) have prohibited this activity, the impacts of past in-channel mining still have to be contended with today.

In France, the ecological and geomorphic impacts of channel degradation have been analyzed in detail, particularly in relation to gravel mining (BRAVARD *et al.,* 1997; BRAVARD *et al.,* 1999). Extensive morphological diagnosis of these problems has been conducted on large rivers, such as those in the

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middle and upper Rhône valley (PEIRY *et al.*, 1994; LANDON, 1996), but few studies are available for the Mediterranean regions of France. Moreover, though the impacts of mining on channel and riparian environments of larger rivers are relatively well documented, little information is available for streams, and little attention has been given to the relationships between mining, streambed sediment deficit, and the sediment balance of coastal zones (TAGLIAVINI, 1978; INMAN, 1985; ERSKINE, 1988). Many studies (PASKOFF, 1998) have pointed out that fluvial sediment transport is the main source of sediment supply to shoreline areas. This is particularly true of Mediterranean shorelines, where beaches are a major source of economic activity.

The aim of this paper is to: (1) assess the impacts of gravel mining on some Mediterranean streams, with regards to both stream bed geometry and granulometry as well as the sediment budget of the beach at their outlet, and (2) examine these results in light of changes that have taken place in their respective watersheds during the last few decades. The study site of Calvi Bay in Corsica was selected because the beach there is eroding, and is fed sediment by two streams, the Fium Seccu and the Figarella, both of which were disturbed by in-channel gravel mining during recent decades.

THE STUDY AREA

The Calvi Bay beach, about 4.5 km long, fringes the inner part of the Calvi Golf in Corsica (Figure 1). The aerial beach averages 25 m in width, but may completely disappear following winter storms.

Beach granulometry varies from east to west: (1) in the east, the present outlet of the Fium Seccu separates two 700 m long pebble beaches that give an average sediment median size of 76.7 mm, (2) a 300 m long active micro-cliff, formed by the erosion of the alluvial fan of the Fium Seccu, averages 88.8 mm (median), (3) another 700 m long beach between the active micro-cliff and the outlet of the Figarella has bi-modal sediment distribution (sands and pebbles), median averaging respectively 59.4 mm for the pebbles and 3.2 mm for the sands, and (4) a beach of fine sand stretches 2800 m between the Figarella and the rocky cape at Calvi, the average median size of the sand decreasing from 2.5 mm in the east to 1.4 mm at the western end (overall average of 1.9 mm). Different studies (BAY *et al.*, 1987; OZER and COMHAIRE, 1988) have demonstrated the continental origin of the beach sediment. The observations show: (1) similarity in petrographic composition between beach and stream sediment, which both contrast with the surrounding shoreline outcrops, and (2) greater similarity between beach sediments and sediments of the Fium Seccu as opposed to those of the Figarella. These studies thus conclude that contemporary sediment supply to the beach is primarily linked to the Fium Seccu.

The Fium Seccu and the Figarella are both Mediterranean streams that drain watersheds comprised of impermeable, resistant, hercynian igneous rocks (RADULESCU, 1991) Their beds are characterized by coarse and even heterometric material, and by steep gradient averaging 0.12 m m^{-1} on the Fium Seccu and 0.08 m m^{-1} on the Figarella (Figure1; Table 1). Channel pattern varies along the stream continuum, with a downstream alluvial cone characterized by multiple unstable channels, typical of montane shorelines.

These streams have high specific stream powers (*e.g.* for Q_2: 292 W.m^{-2} on the Figarella and 343 W.m^{-2} on the Fiume Seccu near their outlets). These values place these streams in the category of braiding streams using the classification of LEOPOLD and WOLMAN (1957).

Their hydrological regime is not well known, but an indirect evaluation may obtained by referring to data for the Fango stream, on which flow levels are recorded at Galéria since 1977. The Fango watershed is just next to the Figarella and has similar characteristics (Figure 1b). This stream has typical Mediterranean regime with severe summer lows, frequent flooding in the spring (April) and the fall (November), and sustained winter flow (max. in January) due to a mixture of rain and snowmelt runoff, as the summits in the watershed exceed 2000 m. Flooding on the Figarella and the Fium Seccu can be assessed by referring to data for the Fango as well as from bankfull discharge measurements made in June 1996. The one in ten year discharge is estimated at 244 $m^3.s^{-1}$ on the Figarella and 120 $m^3.s^{-1}$ on the Fium Seccu (BCEOM, 1997).

MATERIAL AND METHODS

Data for this study has been obtained from: (1) analysis of available technical documents (archives, plans, old topographic surveys. . .), the use of aerial photographs and maps from different dates, (2) field measurements (floodplain and beach geometry, granulometry, sediment displacement).

Recent Geomorphological Change

Coast line changes (DOLAN *et al.*, 1991) were studied on black and white air photos taken in 1960 and 1996 at mean scales of 1/29 000 and 1/27 000 at sea-level. These photos were taken during the summer, when beaches are most developed. The photos were geometrically corrected by referencing to anchor points using the software ERDAS.IMAGINE. Forty-five anchor points (26 in 1960 and 19 in 1996) were chosen along the coast line. The mean margin of geographical error after correction is about 10 m, concurring with the observations of DURAND (1999) in referencing photos to a 1/25 000 topographic map. The coastline was measured every 100 m on each air photo series to map changes between the two dates. The sediment deficit (D) is estimated using the formula (1) based on assessment of the beach surface area lost between 1960 and 1996 (L), estimation of the berm height (h) and the depth of closure (d).

$$D = L\,(d + h)/2 \qquad (1)$$

L was determined from measures made on air photos, h was estimated to be equal to 0 based on observations derived from twelve beach profiles. Values retained for depth of closure (d) vary between − 6 and −8 m (FARNOLE, 1996).

The width of the active channel (low water channel and unvegetated bars) and bank height were measured every 300 m starting from the outlet for a distance of 4500 m on the Fium Seccu (17 stations on 28 % of the total length of the main channel) and 7 500 m on the Figarella (24 stations on

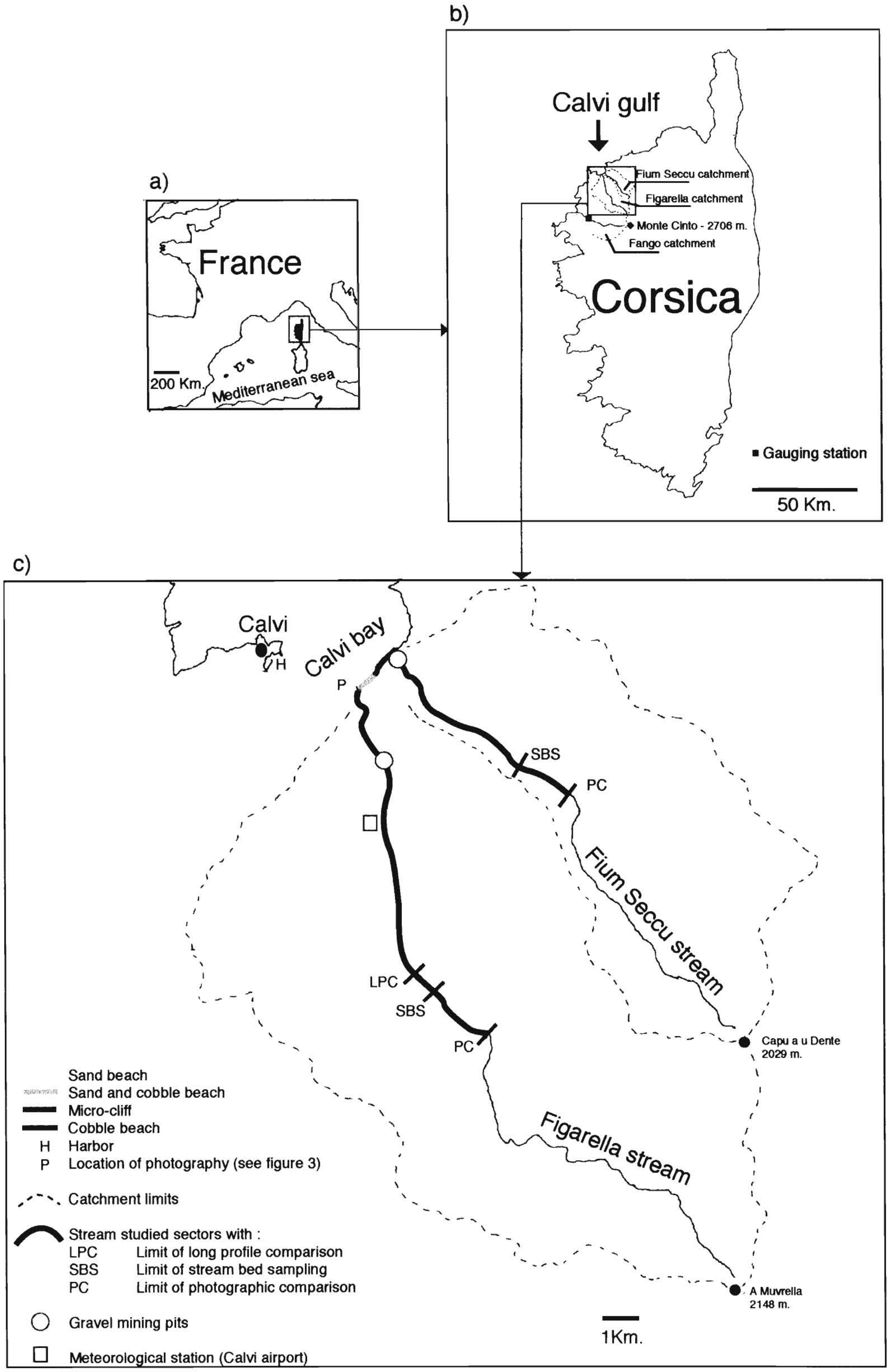

Figure 1. Location of the study site in France (a), in Corsica (b), in the Calvi Bay (c).

Table 1. *General characteristics of the two watersheds.*

	Fium Seccu	Figarella
Watershed area (km^2)	63	137
Length of the main stem (km)	16	24
Drainage density (km/km^2)	1.63	1.56
Elongation ratio	0.64	0.70
Relief ratio	0.14	0.11

30% of the stream). Channel gradient was determined for each station using available long profiles for the two streams.

On the lower 9 km of the Figarella (*i.e.* 37% of total length), two existing long profiles were compared. The first was taken from a 1/5,000 topographic survey made in 1963 for DDE (Direction of Equipment) and the second mapped at 1/5,000 in 1991 for BRGM. On the Fium Seccu, only one long profile was available, made on 5700 m (37% of the total length) by BCEOM in 1997. As this profile does not concern the outlet of the stream, where a wooded mining pit is located, we therefore completed this profile with our own field data including a long profile and six topographic cross-sections 500 m apart on the lower section of the stream (April 1997). To estimate the volume of the excavation, bores were made in the accumulation of fine sediments (6 along the downstream cross-section, and 10 distributed along lower 100 meters off the long profile). The diameter of the alders which colonised the pit was measured. Their age was also determined using dendrochronology to date the recolonization.

Sediment Analysis

Fourteen sand samples were collected every 200 m at mid-aerial beachface position, as this is the most significant sampling site (MASSELINK, 1992). In sectors with pebbles, samples were spaced every 100 m. The B axis was measured on 25 randomly sampled pebbles along cross-sections perpendicular to the beach. Where a mixture of sand and pebbles was present along cross-sections, sand was also sampled.

Bed geometry and the size of pebbles were also measured in the stream beds at the forementioned stations; at each one, the B axis was measured on 50 elements (D), randomly sampled along cross-sections perpendicular to the channel (KELLERHALS and BRAY, 1971). For each station, two granulometric indicators (Φ_{50} and the sorting index S_t (2)) were calculated, the Φ scale (3) being used to attenuate the distortions in size induced by the larger elements (GORDON *et al.*, 1992).

$$S_t = \frac{(\phi_{84} - \phi_{16})}{2} \tag{2}$$

$$\phi = -\log_2(D). \tag{3}$$

The surface samples of the 16 bores made in the gravel pit on the Fium Seccu were analyzed in the laboratory, mean grain size being estimated using the statistic moments method (MASSELINK, 1992). Granulometry of gravel forming bars and fans in the wooded mining site were also measured using the above-described procedure.

Further sampling was done during the June 2nd, 1997 bankfull flood using a manual depth-integrating sampling system (TASSONE *et al.*, 1992), enabling measurement of sediment concentrations transiting in suspension and by saltation. Discharge was also measured during this event on two cross-sections located 800 m (Figarella) and 500 m (Fium Seccu) from the outlets. At the same sites, bedload transport was evaluated by painting gravels along a meter wide strip across the entire width of the active channel (about 20 m) to assess gravel migration distance during the flood event. Cross-sections were also measured before and after the flood to evaluate the depth of the sediment wave. Flood water levels were determined by measuring the maximum relative height of debris, and by direct observation (flood of June 2nd, 1997 on the Figarella) in order to determine the wetted area as well as the flood discharge.

Evolution of Control Parameters

Drainage basin characteristics were assessed using digitized layers derived from IGN 1/100 000 topographic maps, and processed with ERDAS IMAGINE. The evolution of vegetal cover was evaluated for individual *communes* (local administrative unit) in the two watersheds by comparing a map from the late 18th century, the mid-19th century Napoleonian land survey (DEFRANCESCHI, 1983; and original data), and the 1988 forestry census of the *Inventaire Forestier National.*

The surface area of the active channel was measured on air photos taken in 1960 and in 1996. As LEWIN (1977) emphasises, mapping channel patterns is an effective means of identifying long term changes in sediment flux and associated variations in discharge regimes. This information was visually interpreted following the procedure described by GIREL (1986). Channel patterns were drawn, digitized, geometrically corrected and set to scale using image processing software (ADOBE PHOTOSHOP). The two dates of observation could thus be compared.

Evaluating hydrological chronics for recent decades was difficult due to a lack of available data,. Three alternatives were considered: (1) referring to rainfall data at Calvi-Airport (1961–1996), (2) extrapolating from the hydrological data for the nearby Fango stream (1977–1996), (3) synthesis of bibliographical data available for Corsica. Major flood events in Corsica have been recorded for the last three centuries (BOERI and GAUTHIER, 1994).

RESULTS

Beach Erosion

The beach was eroded 10 m on average between 1960 and 1996, corresponding to a loss of 40% of the initial surface (Figure 2). Certain buildings close to the beach have been periodically destroyed by storms such as those in May 1992 and February 1996 (Figure 3). Only the sector located 3.5 km from Calvi, corresponding to the alluvial fan of the Fium Seccu, has remained stable (Figure 2).

Beach erosion is particularly apparent near the two stream outlets, especially to the west of them. Here beach erosion is estimated at 15 and 25 m respectively at the outlets of the Fium Seccu and the Figarella. As the longshore current is

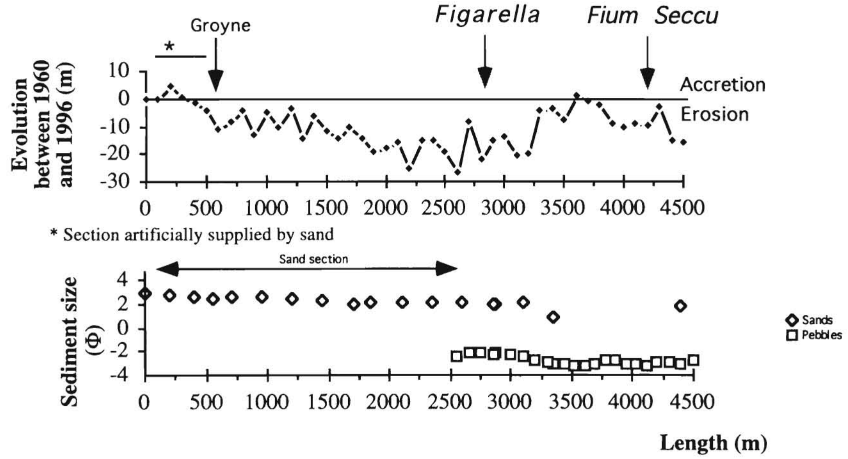

Figure 2. Evolution of beach width in Calvi Bay between 1960 and 1996 (a) (from air photos) and present variations in grain size (b).

from east to west, this demonstrates that the sedimentary deficit of the beach is linked to fluvial supply decrease.

Beach erosion of about 30 m has also been shown for the period 1951–1990 in the western part of the bay, near the Calvi port (OLIVEROS *et al.*, 1997). This is not apparent in Figure 2 because 15 000 m^3 of artificial fill was added to 900 m of the beach. The erosion of this part of the beach is primarily explained by laterally expanding or agitated currents caused by the deflection of the northeasterly surge against the port jettie, built in 1977 (FARNOLE, 1996).

Between 1960 and 1996, beach surface had decreased by about 50 000 m^2. Global sediment deficit varies between 150 000 and 200 000 m^3, averaging roughly 175 000 m^3 (4861 m^3 yr^{-1}). The beach lost roughly 40 000 m^2 to the west of the stable alluvial fan abandoned by the Fium Seccu (Figures 1 and 2) compared to 10 000 m^2 to the East. Thus the sediment deficit to the west attains 120 000 to 140 000 m^3 opposed to 30 000 to 40 000 m^3 in the east. Our results are inferior to but comparable with those obtained by comparing bathymetric DTM data (FARNOLE, 1996) in the sandy part of the bay for a shorter period (1990–1996), results which give a mean annual deficit of 7500 m^3 yr^{-1}.

Gravel Mining Sites

Gravel pits were located in the active channel of the streams studied (Figure 1).

The oldest gravel pit, located at the outlet of the Fium Seccu was officially exploited from 1967 to 1970. A 300 m long section of the stream was directly subject to excavation, cor-

Figure 3. Photograph of beach near the Olympic camp (see Figure 1c for location).

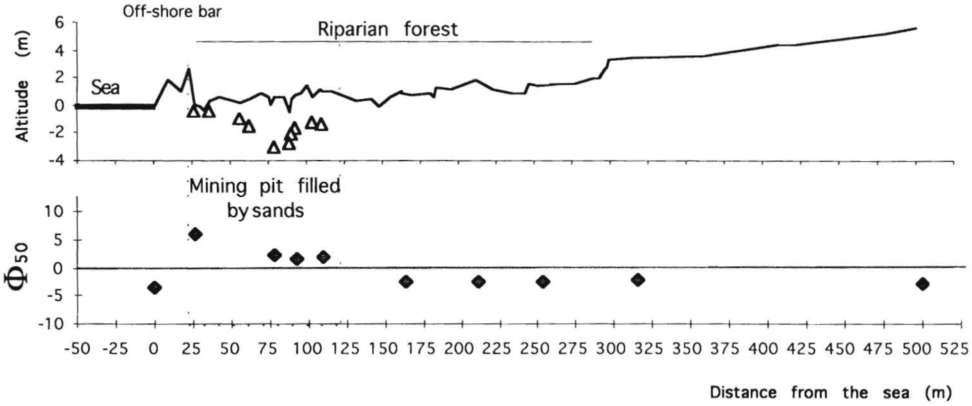

Figure 4. Effects of the gravel pit on the long profile and sediment pattern on the lowest 500 m of the Fium Seccu.

responding to a surface area of 1.5 ha (Figures 4 and 5). Following its abandonment, this site was rapidly re-colonized by alluvial forest of alder trees averaging 22 years of age (Figure 5). Results of the 15 bores made in the fine sediments trapped in the lower part of the excavation show that the gravel pit was three meter deep. The total mining volume is estimated at 20 000 m^3. Data from bores indicates that 15 000 m^3 of fine sediments have accumulated in the pit.

A second gravel pit was opened in 1972 in the lower section of the Figarella, 3 km from the outlet, and operated until 1992. By comparing long profiles and channel patterns, the excavation area was estimated to be about 200 000 m^2, corresponding to a volume of about 600 000 m^3; (200 m large, 3 m deep, and 1 000 m long).

A third gravel pit was exploited without authorization downstream of the second one between 1975 and at least 1985 (the most recent summons established by the mayor's office pertaining to the matter being dated to 1985). The volume extracted from this pit remains unknown, but the impacts of this exploitation are evident in the field.

Impact of Mining on Stream Beds and Sediment Transit

The excavation on the Fium Seccu is evident on the 1997 long profile (Figure 4); its maximum depth is close to -3 m. Alder growth has affected long profile upstream of this site, significant aggradation being linked to increased vegetation roughness (Figure 4). Longitudinal distribution of sediment size in the forested zone shows transition between gravel deposits in the upstream area (roughly one third of the surface) to sand and silt downstream, the lowest section being characterized by a mosaic of islands of silt and sand intermingled with swampy areas (Figures 4 and 5). The micro-topography of this zone illustrates the filtering effect of the vegetation. The gravel in the upstream part of the pit is deposited in bars whose number and size decrease regularly downstream, where fans of coarse sediment thin out and disappear as they penetrate into the forest. Micro-morphological analysis thus indicates that most of the fine sediments which would have normally fed the beach have been trapped in the excavated zone since 1972.

Because the lowest 100 m of the stream only receive sand and silt, the supply of gravels and cobbles to the beach can be considered as null. The Φ_{50} of the beach at the outlet is much greater than those measured on the stream, indicating that the supply of bed load has been interrupted for a long period of time. Indeed, during the flood observed on June 2nd, 1997, no painted cobbles transited into the section colonized by the alder forest. Our results contradict those of BAY and al. (1987), who considered that some supply of "fresh" gravel subsists. The supply of fine sediment is also greatly reduced, as most of the fine sediment in transit is trapped in the pit before reaching the coastline. Nonetheless, some supply to the beach does occur, as suspended load measurements made during the flood of June 2nd, 1997 (25 $m^3 s^{-1}$) gave values of 1830 $g\ m^{-3}\ s^{-1}$ upstream of the alder forest and 567 $g\ m^{-3}\ s^{-1}$ downstream of the forest.

This mining site does not appear to have had a major impact on the granulometry of the section immediately upstream of the pit (Figure 6). Bed width, gradient, and bank height are linked, bed width and bank height increasing downstream, whereas gradient decreases. Granulometry on the Fium Seccu does not show longitudinal change, particularly in comparison to the Figarella. The Φ_{50} and the S_i show little variation from one station to the next; the ranges of these variables are respectively -1.14 (Φ_{50}) and -0.92 (S_i) on the Fium Seccu as compared to -2.63 (Φ_{50}) and -1.28 (S_i) on the Figarella (Figures 6 and 7). Most of the stations on the Fiume Seccu show more homogeneous and smaller sediment size for a given slope, compared to data for the Figarella. Bed cleaning of a 1 km section upstream of the bridge on route N197 done by the DDE appears to affect the granulometry of the stream bed more than that of the gravel pit: (1) in the cleaned section, bed load is relatively fine and becomes increasingly fine and homogenous downstream, i(1) just upstream of the cleaned section, granulometry is much coarser and shows signs of bed armoring.

The gravel pit on the Figarella figures on the 1991 long

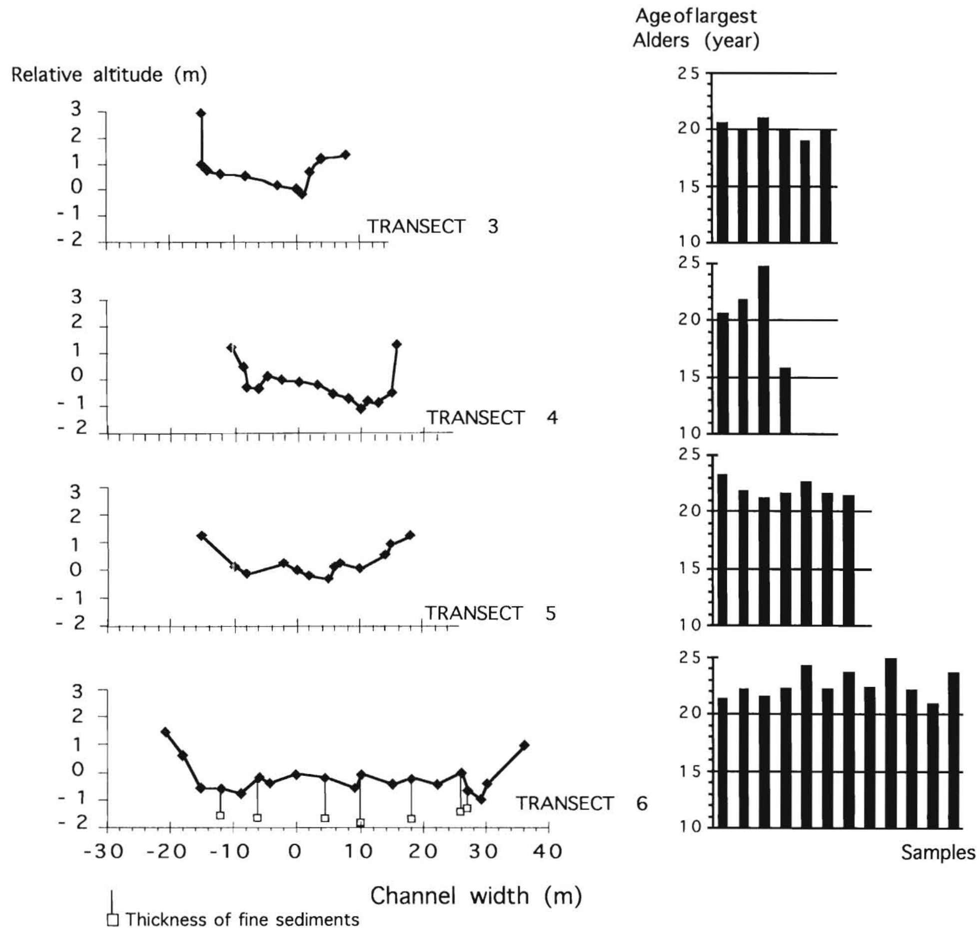

Figure 5. Cross-sections of the gravel pit on the Fium Seccu and age of alders. *See Fig. 4 for locations.*

profile of this stream (Figure 7). Data from sampling stations (5 are located within the excavated section), demonstrate that this pit disrupted both bed geometry (gradient, bank height, width) and granulometry (Φ_{50} and Φ_{84}). Gradients measured in the mining zone differ from gradients observed on the other parts of the stream. There is thus very weak linear relationship between gradient and the distance to the sea ($r^2 = 0.17$). The steepest gradient and the mildest gradient are respectively located in the upstream and central parts of the pit. The relationship W = f(S), established on the Fiume Seccu does not hold on the Figarella (Figure 8a). 3 distinct reaches were identified: (1) part of the pit reach is characterized by steep gradient and varying widths, (2) the most downstream reach is remarkable for its narrowness and mild gradient, (3) other sections present values of S and W similar to the those observed on the Fiume Seccu. Bank heights in the mining zone are lower than those on the reset of the studied reach. In the excavated area, the active channel is beginning to take form within a vegetated floodplain that is not yet fully developed either. In contrast, banks are relatively high both upstream and downstream of the mining site. A statistical relationship is observed between H and W ($r^2 = 0.32$, $p = 0.025$) (Figure 8b) when data from the excavated section is excluded from analysis.

Mining has also affected granulometry. The upstream—downstream distribution of median particle size and of the sorting index show the impact of the pit on bed load transit: (1) the mining site registers fine and relatively heterometric distribution i(1) just upstream and downstream of the mining site, reaches show coarse and equally heterometric grain size. Sizes are among the largest observed in the entire stream course, and much larger than those observed on the Fiume Seccu. Variations of the median along stream continuum indicate regressive and progressive erosion in association with armoring: Φ_{50} increases over 2 km upstream of the pit and decreases progressively in the 2 km downstream of it. Moreover, Φ_{84} increases with gradient ($r^2 = 0.31$) confirming the armoring process observed upstream of the mining area.

Regressive (on 2500 m) and progressive (on 500 m) erosion of the stream bed have led to the abandonment of secondary channels, producing a fluvial metamorphosis from a braiding pattern to a single-bed channel.

Observations made during the June 2nd, 1997 flood (100 $m^3.s^{-1}$, that is a relatively frequent event, just barely over-

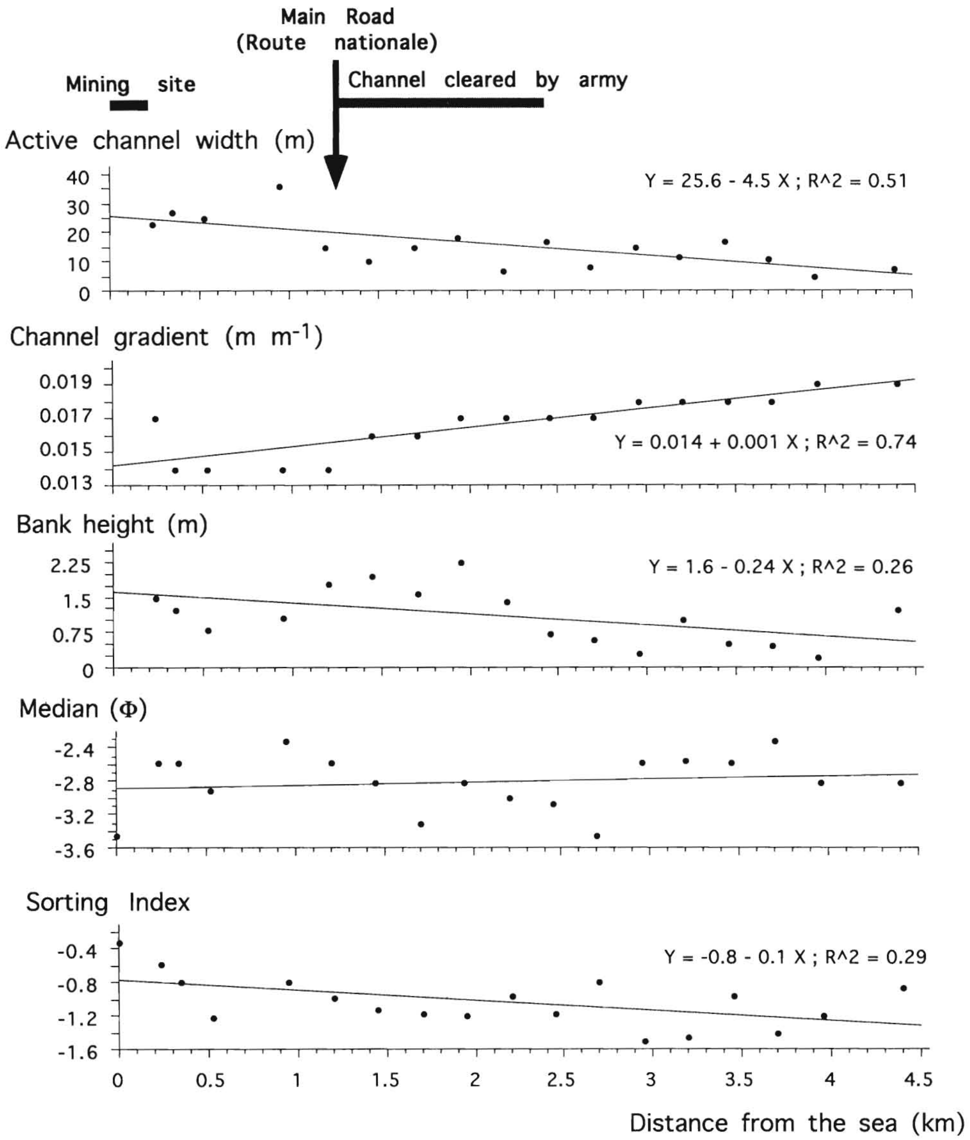

Figure 6. Longitudinal variation of active channel width, gradient, bank height and sediment size on the lower 5.5 km of the Fium Seccu.

flowing at the point of observation) showed that sediments as large as 13 cm (D_{90}) in diameter were mobilized, displacing a volume of 10.9 m^3/km^2 compared to 10.3 on the Fiume Seccu. Measures of sand transport were also made, indicating suspended or saltating transit of 3.8 $kg/m^3/s$ downstream of the gravel pit.

In conclusion, the mining site continues to trap sediment, implying that the coast is only supplied in sediment by the section downstream of it, whereas this latter is already affected by armoring processes.

Evolution of Control Parameters

Although the impact of the mining sites has been demonstrated, this does not exclude the intervention of other factors in explaining the current sediment deficit of the coastal zone. Indeed, it is rather surprizing that Mediterranean streams are not able to check the expansion of riparian forests into their active channels. The hypothesis of an eventual decrease in hydrological activity must be verified. Several elements may serve this purpose:

- the available hydro-climatic data is unfortunately rather incomplete. Records of flooding having provoked damage since the early 18th century indicate a period of frequent flooding during the 19th century. More than 25 % of all the floods recorded since the beginning of the 18th century on 5 streams in the surrounding area took place between 1850 et 1900, whereas less than 10% of all the floods took place during the first half of the 20th century. No specific tendency has been observed in the recent data sources available: (1) instantaneous discharge measurements during

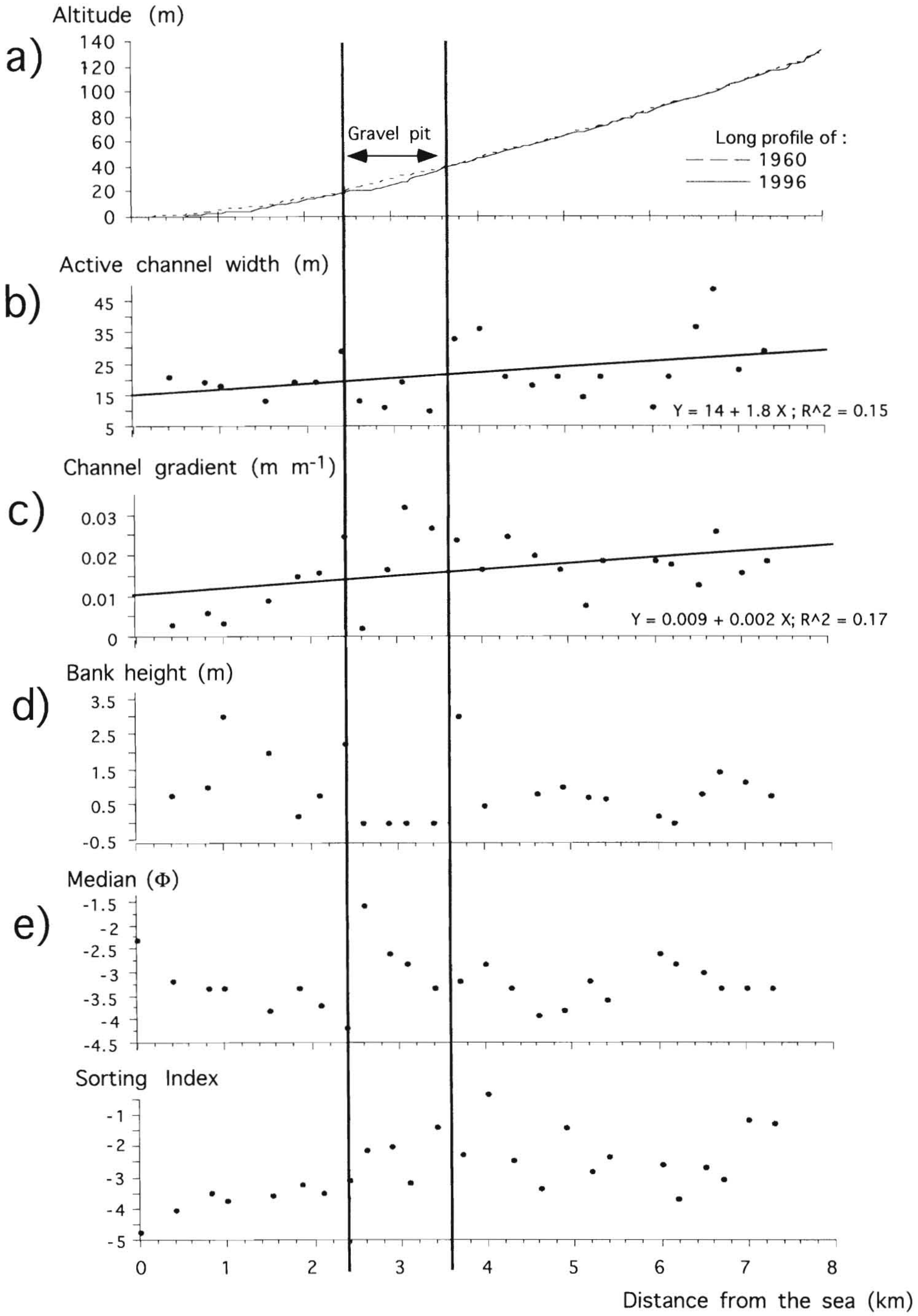

Figure 7. Longitudinal variation of channel altitude in 1963 and in 1991 (a), of contemporary active tract width (b), gradient (c), bank height (d) and sediment size (e) on the lower 7.5 km of the Figarella.

floods on the Fango between 1977 and 1996, (2) yearly rainfall maximums and frequency of days of more than 30 mm per day in data from the Calvi—Ste Catherine meteorological station (Figure 9).

- the channel patterns of the lower sections of the two streams have undergone considerable changes between 1960 et 1996, not only within the mining sites, but along the entire length of their downstream reaches (Figure 10). In particular, the active channel width of the Fium Seccu has narrowed from 19 m to 8 m of stream during this period.
- changes in land use may have an added effect on the im-

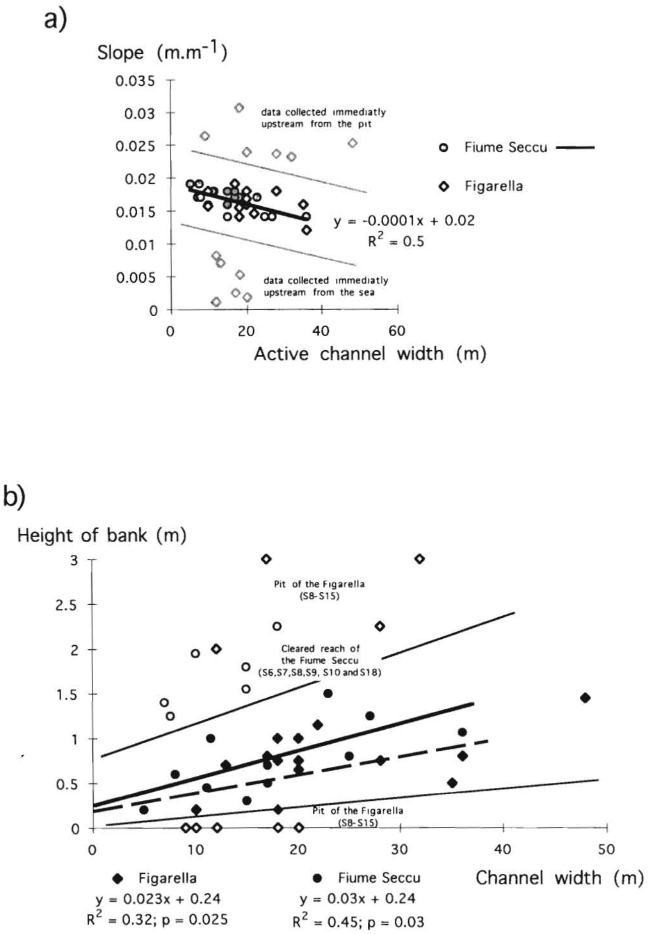

Figure 8. Relationships between active channel width and (a) gradient or (b) bank height. Data from 47 observation points on the Figarella and the Fium Seccu made at regular intervals, 300 m apart.

pact of the mining sites in relation to the problem of coastal sediment deficit. Evidence of extensive abandonment of agricultural lands was obtained for both watersheds during the 20th century. Analysis of the nature of vegetal cover in the watersheds based on the above-mentioned late-18th century archives, the mid-19th century Napoleonian land survey, and the 1988 forestry census shows that the hillslope soils are much more protected today then they were a century ago (Figure 11). The part of cultivated lands in the watersheds of the Fium Seccu and the Figarella were respectively 81% and 48% in the middle of the 19th century, and have decreased to 18% and 16% today.

DISCUSSION

The Causes of Sediment Deficit

Decreases of sediment delivery by major streams to the shoreline is a serious problem that affects the entire northern coast of the Mediterranean basin (GUILLEN and PALANQUES, 1992; INNOCENTI *et al.,* 1993; POULOS *et al.,*1996). The causes of this phenomenon are complex, particularly on large rivers, because of the great number of factors—damming being one of the foremost—which play at varying spatial and temporal scales depending on their location, extent, or number within the drainage network (KOMAR, 1996).

By focusing on smaller streams, our study has once again demonstrated a reduction in sediment supply, but it has highlighted the relative importance of each of the causes as they are less numerous. Indeed only two factors have been shown to be possible explanations of decreased sediment supply to the shoreline: gravel mining in streams beds, and land use changes in the watershed. The observed coastal sediment deficit is apparently linked to changes in these fluvial systems as the most eroded parts of the shoreline are near the stream outlets. The global sediment deficit of the coast has been estimated at 4 800 $m^3 yr^{-1}$. Only the eastern part of the deficient beach area (20% of the total deficit) is comprised of coarse material (a shingle beach overlaying underwater sand deposits). Therefore, more than 80% of the deficit corresponds to a lack of sand.

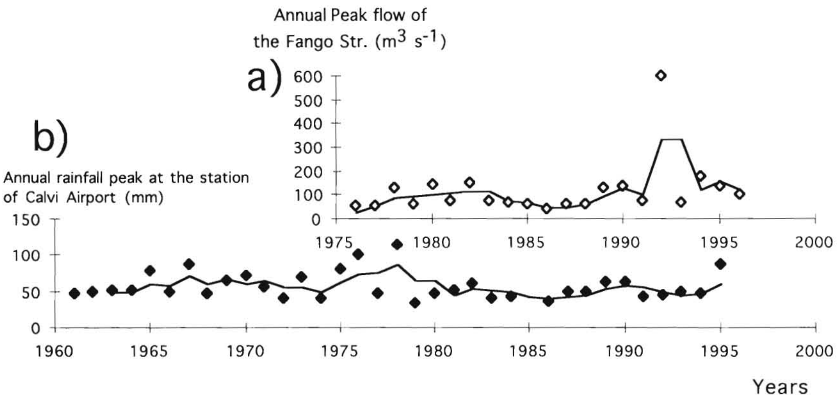

Figure 9. Evolution (a) of annual peak flow on the Fango at Galéria-Ponte vecchio (129 km^2) since 1977 and (b) daily rainfall record per year at Calvi-airport since 1961.

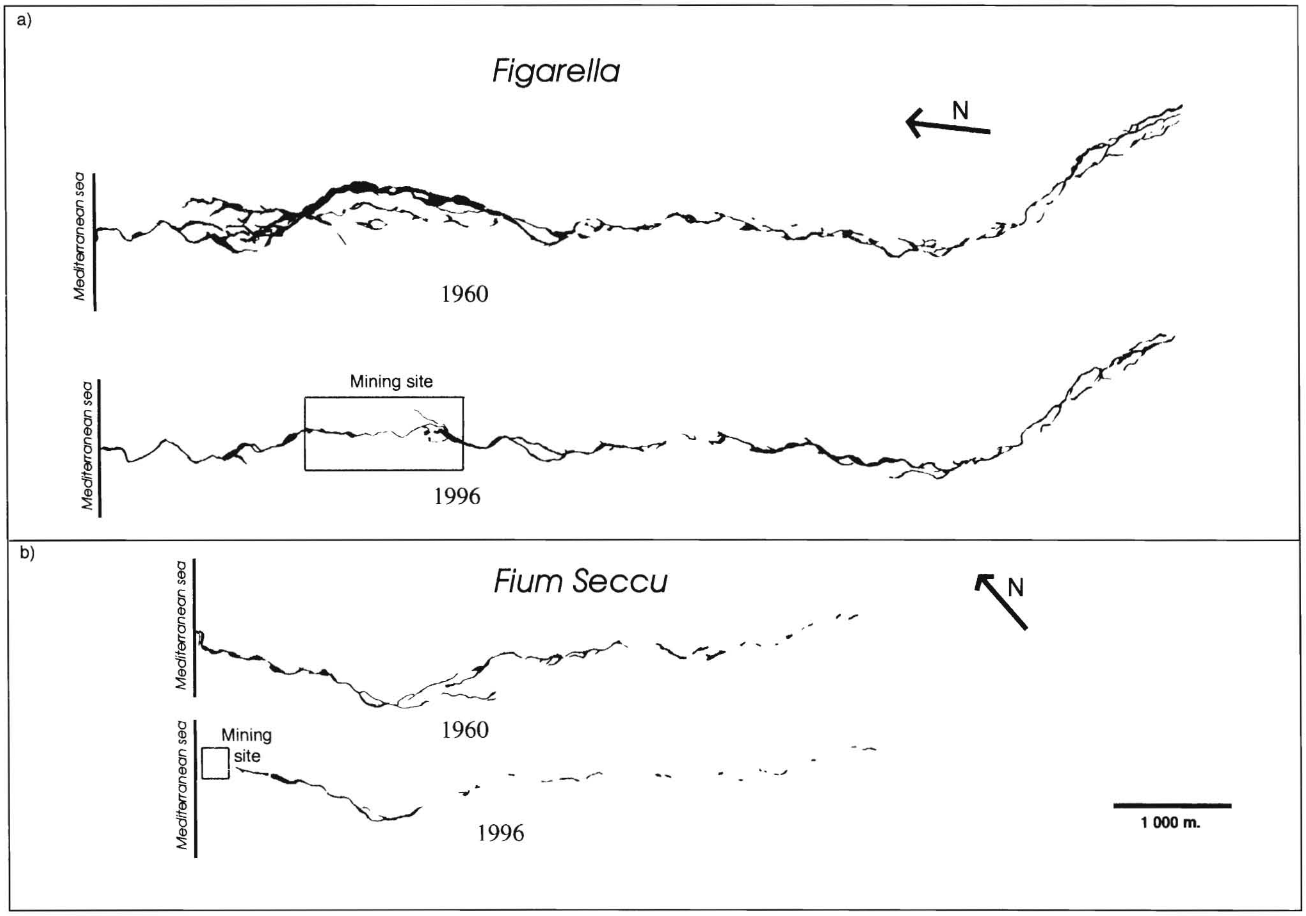

Figure 10. Evolution of active channel surface area on the Figarella (a) and the Fium Seccu (b) between 1960 and 1996.

The impacts of the gravel pits on sediment transit were evaluated from geomorphic and sedimentary data that may be compared to other observations in literature. The volume of sand and silt trapped in the Fium Seccu excavation was estimated at 15 000 m^3 for a period of 29 years, giving an annual average input of 517 $m^3.yr^{-1}$ (Table 2). This figure is smaller than those given by other sources indicating an overall suspended sediment production in Corsica of roughly 14 $m^3.km^{-2}.yr^{-1}$, that is 882 $m^3.yr^{-1}$ (QUELENNEC *et al.*, 1982; and Table 2). Evidence that part of the suspended load does pass through the forested mining site of the Fium Seccu and reach the beach (31% of total suspended load input during the June 2nd, 1997 flood) may explain this difference in figures.

If the sand supply were entirely cut-off by the gravel pits on the Fium Seccu and the Figarella, the resulting annual sand deficit would be respectively within the forks of 517–882 m^3 and 1124–1918 m^3 (Table 2). The upper limit given here is undoubtedly over-estimated, given the implications of our field observations on the Fium Seccu. Inversely, the lower limit is clearly under-estimated, as the gravel pits did not trap all of the incoming sediment. These figures indicate that the sand deficit due to gravel mining is not greater than 2500 $m^3.yr^{-1}$. This volume is by far inferior to the volumes displaced annually by coastal processes. Furthermore, it is not unreasonable to consider that the coastal deficit due to reduced fluvial supply was probably attenuated by input from alternative sources:

(1) sand continued to transit beyond the gravel pits, as shown by measurements made during the flood of June 2nd, 1997,
(2) during gravel mining, sand in the pits was disturbed, provoking some transit of suspended elements downstream,
(3) on the reach of the Figarella below the gravel pit, sediments were mobilized during the winnowing process and channel degradation due to erosion induced by watershed sediment deficit.

Although gravel mining only partly explains the current sediment deficit of the shoreline, the long-term implications should not be neglected. The gravel pit on the Figarella is still apparent on the long profile and is far from being completely filled in. It should take at least 360 years for the profile of the Figarella to fully recover from the disturbances caused by mining (Table 2).

The volume of sediment trapped by the gravel pits being

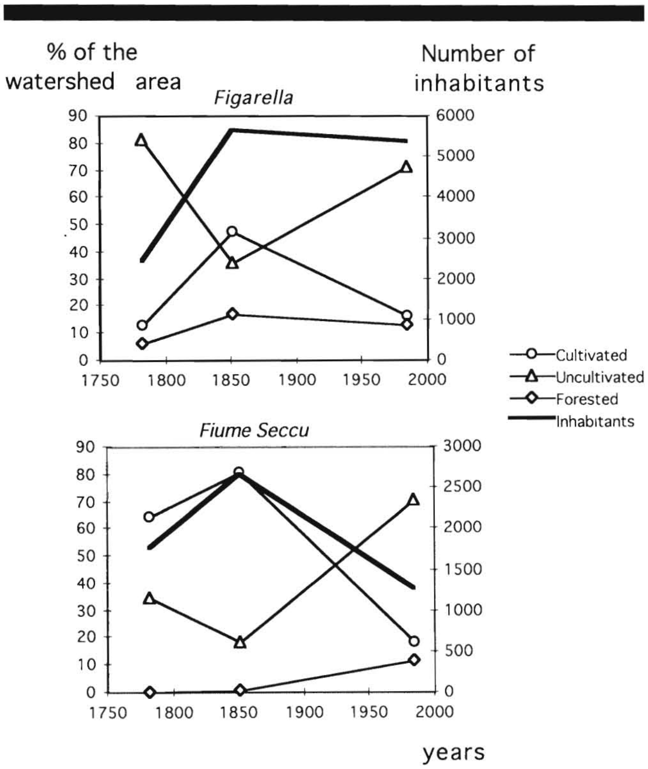

Figure 11. Evolution of watershed land use for the Figarella (a) and the Fium Seccu (b) since the late 18th century. Based on the *plan Terrier*, the *Cadastre Napoléonien* 19th century survey, and census data from *l'Inventaire Forestier National*.

Table 2. *Sediment delivery and gravel pit excavation capacities.*

	Fium Seccu	Figarella
Measurements		
Volume extracted (m^3)	20 000*	600 000
Years since extraction began	29 years	24 years
Measured annual suspended load	517 $\text{m}^3\cdot\text{yr}^{-1}$	1124 $\text{m}^3\cdot\text{yr}^{-1}$(a)
Annual suspended load per unit area	8.2 $\text{m}^3\cdot\text{km}^2\cdot\text{yr}^{-1}$	8.2 $\text{m}^3\cdot\text{km}^2\cdot\text{yr}^{-1}$(a)
Data extrapolated from Quelennec (1982) and SOGREAH (1987).		
Suspended load per unit area (b)	14 $\text{m}^3\cdot\text{km}^2\cdot\text{yr}^{-1}$	
Bed load per unit area (c)	2.8 $\text{m}^3\cdot\text{km}^2\cdot\text{yr}^{-1}$	
Annual suspended load	882 $\text{m}^3\cdot\text{yr}^{-1}$	1918 $\text{m}^3\cdot\text{yr}^{-1}$
Total annual bed load	1058 $\text{m}^3\cdot\text{yr}^{-1}$	2301 $\text{m}^3\cdot\text{yr}^{-1}$
Number of years required to fill the pit		
according to measured suspended load	29 yrs	364 yrs
according to extrapolated total bed load	19 yrs	260 yrs

* 15 000 m^3 filled by sand deposit

(a) assuming that load per unit area is equivalent to those of Figarella.

(b) assuming a suspended load of 35 t km^{-2} yr^{-1} at a density of 0.4 (sand).

(c) assuming that bed load is equal to 20% of the suspended load.

much smaller than the volume of sediments lost by the beach, changes in land use may be a second cause of sediment deficit. Indeed, other studies in the Mediterranean basin have stressed the implications of land use changes in relation to sediment budgets, notably in the Spanish Pyrenees (MOLINILLO *et al.*, 1997) or in southeastern France (PIÉGAY *et al.*, 1997; LIÉBAULT *et al.*, in press). Moreover, the effects of land use change may be enhanced by climatic change, particularly the end of the Little Ice Age in the late 19th century (GROVE, 1988).

Channel patterns have changed on the streams studied here, even on the Fium Seccu which registers no evidence of significant recent bed incision. Both of these basins have been subject to agricultural abandonment, implying that the recent sediment deficit may in fact be linked to a long term decrease in sediment production associated with changes in channel dynamics and pattern. Mining would have thus deprived the outlets of a fossil sediment resource which could have temporarily supplied the beach by longer term bed incision. Field measurements have shown that roughly 15% of the material mined from the Figarella was sand, implying that the pit on the Figarella deprived the beach of roughly 90,000 m^3 of sand, that is 4,500 m^3 yr^{-1} (20 years of mining) which coincides well with our estimates of sand deficit for the shoreline.

It would be hasty to conclude that the erosion of Calvi beach is due exclusively to gravel mining, as other possible causes, both local (ports and shoreline building development) and global (land use changes, climatic change, or even sea-level change) may also contribute. However, the results discussed here demonstrate that gravel mining is a major cause, and probably the main one. Gravel mining can severly limit the delivery of sediment to the coastal environment, in a manner similar to that of damming, as discussed by BROWNLIE and TAYLOR (1981) and INMAN (1985) on the coast in southern California, or FRIHY *et al.* (1991) on the Nile.

Fluvial Response to Gravel Mining

The fluvial systems studied here register original responses to changes induced by gravel mining.

The dynamics of alluvial forest development within the active channel of the Fium Seccu are quite unusual. In southeastern France, generalized expansion of riparian forests has been observed in conjunction with channel narrowing (PIÉGAY and SALVADOR, 1997), but no case in which the active channel has disappeared entirely, has been reported. This remarkable phenomenon observed on the Fium Seccu may be explained by:

(1) a favorable physical environment. Recently, no major floods capable of destroying the forest have occured and therefore sediment transport has been limited. The particularly mild gradient of this section does not enable bed load to transit to the shoreline, most of it being deposited upstream in an aggrading reach characterized by diverging channels.

(2) human modification of this environment has produced a particularly humid biotope comprised essentially of fine sediment, ideal for Alders (PAUTOU, 1984). This biotope would rarely occur naturally on Mediterranean streams.

The impacts of mining are clearly identifiable on the long profiles of the Figarella. Degradation attenuates as the distance from the gravel pit increases, similar to observations made on the Ubaye or the Giffre (PIÉGAY and PEIRY, 1997). Moreover, grain size is also affected. Indeed, small mountain streams often have heterogeneous granulometry, more likely to evolve in response to profile modifications, whereas larger rivers, such as the peri-alpine tributaries of the middle Rhône, have abundant bedload and homogeneous granulometry, typical of braided piedmont rivers. On large rivers, homometric sediments are moved at once without sorting, and thus geomorphic response concerns mainly bed geometry (degradation and reduced width in particular) but less often grain size changes

On the Figarella, channel incision provoked downstream winnowing as described by CARLING (1981), a process of selective scouring which displaces smaller material while coarser elements remain unaffected by tractive forces. As explained by KOMURA and SIMONS (1967), degradation ceases when bed D_{50} is approximately equal to D_{90} before degradation began. Sediment size was measured in one of the main active channels before mining and in the main channel after mining. The D_{90} of the abandoned channel was close to the D_{50} of the actual channel in 4 of 5 samples (11.95 cm on average vs. 11.12 cm). Bed degradation and therefore armoring thus appear to be well advanced, sedimentary channel adjustments to recent morphological change being nearly completed at certain points of measure. Winnowing processes are enhanced on such streams because bed material is heterogeneous. Scour preferentially winnows the finer fraction and the surface is protected by the coarser elements against further erosion (GARDE *et al.*, 1977). This armoring process has rarely been described within a context similar to this study. RICHARDS and CLIFFORD (1991) point out that this process is traditionally emphasized as a mechanism associated with the secular disequilibrium of streambed degradation, such as below reservoirs. However, other cases armoring in which degradation digs down to bedrock or underlying coarser substrates have already been documented, both downstream and upstream from gravel pits (DIETRICH *et al.*, 1989) or more commonly, downstream of dams (ASSANI, 1997).

In comparison to the Figarella, the effect of mining on geometry and sediment transit seems to be less remarkable on the Fiume Seccu. This may perhaps be explained by the differences in the location, duration, and lapse of time since the abandonment of these two gravel pits. The excavation on the Figarella is still occasionally exploited whereas the excavation on the Fiume Seccu was abandoned in 1972. The pit on the Fiume Seccu being located near the stream outlet and practically at the sea level, the impacts are only apparent upstream of the pit, and even then only moderately. Given the age of the pit and the high roughness of the channel at the outlet of the Alder forest, the profile seems more affected by aggradation than by degradation. The bed load is also finer and more homometric than on the Figarella.

The results presented here diverge with the conclusions of BAY *et al.* (1987) and COMHAIRE (1988), according to whom current sediment delivery to the beach comes primarily from the Fium Seccu, simply because of human modifications. The combination of the excavation and the alder forest development form a highly effective sediment trap. The general characteristics of the Fium Seccu and its drainage basin do tend to indicate that this hydrosystem is better adapted to delivery sediments to the coast than that of the Figarella in spite of a smaller drainage area (better relief ratio, more adequate form, better drainage, more weathered substratum (transition from leucocratic granits in the west to monzogranits with more biotites and less silice in the east). This is confirmed by channel morphology: the alluvial fan of the Fium Seccu is larger than the fan on the Figarella, the bed of the Fiume Seccu is less degraded, and bed load in transit is abundant, implying that some channel cleaning is required. Moreover, land deforestation has been historically more frequent in the Fiume Seccu basin than in the Figarella basin.

The consequences of the alder forest development in relation to the changes in sediment transit dynamics following the abandonment of the gravel pit are thus an important issue. Even when the long profile will have returned to a new state of equilibrium (which will soon be the case, given the channel adjustment already accomplished), the prior conditions of sediment transit will not be restored because of the forest. This section now looks like a cut-off channel in a way because flow is intermittent during part of the year, and flooding is highly irregular (high water levels do not occur every year). There is therefore a risk that a sort of "organic and sedimentary plug" may develop here, keeping floods from renewing the fluvial mosaic in the alder forest. In this case, upstream constructions (road and railway, military base. . .) would probably be endangered.

CONCLUSIONS

The sediment deficit of the Calvi beach is the result of reduced continental sediment input from the basins of the Figarella and the Fium Seccu. Although the delivery of fine and coarse sediment is possible, given the hydro-climatic and geomorphic characteristics of these basins, the in-channel gravel-mining pits trap almost all of the sediments in transit, even years after mining itself has been stopped. Moreover, the impacts of mining coincide with a contemporary deficit in sediment supply, typical of northern Mediterranean mountainous river systems, due essentially to agricultural abandonment and increased vegetal cover of watershed hillslopes. The original aspect of this case is that the impacts downstream of the stream system affect the heart of regional economy: the Calvi beach is a central resource to leisure activities. The problem is thus somewhat different from the examples taken in the Rhône basin, where reduced sediment transit has made it very difficult to mitigate bed incision intensified by gravel mining, lowering the levels of floodplain water Tables, and causing serious damage to bridges and dikes (BRAVARD *et al.*, in press).

In a management perspective, several possible actions merit consideration:

(1) Gravel mining in French rivers is already prohibited, but this must be strictly enforced. In some cases, cleaning may be necessary to avoid undesirable channel instability in developed areas, (particularly to protect a military

base on the left bank of the Fiume Seccu), but the cleaned sediment should serve to feed the beach.

(2) The question of whether or not the riparian forest should be left in the active channel of the Fium Seccu must be dealt with rapidly as Mediterranean floods may be extremely violent, like in 1993 in southern Corsica (Loye-Pilot and Pasquier, 1994). Two alternatives seem plausible, either the forest should be cut even though it is a natural environment of exceptional structural and functional value (turtle nesting. . .), or else a second channel should be created to divert floods along the left bank of the floodplain.

(3) Beach erosion must be considered as inevitable to planners and development reoriented accordingly, because even if various alternatives may slow this process, it is unavoidable in the long run.

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REFERENCES

Assani, A.A., 1997. Recherche d'impacts d'une retenue sur le comportement d'une rivière ardennaise (hydrologie, sédimentologie, morphologie et végétation). Cas du barrage de Butgenbach sur la Warche (Belgique). Doctorate thesis, Faculté des sciences, University of Liège, Belgium, 482 p.

Bay, D.; LeJeune, A.; Nihoul, J., and Ozer, A., 1987. *Etude de l'érosion de la plage de la baie de Calvi.* STARESO, 194p.

BCEOM (Bureau Central d'Etudes pour les Equipements d'Outre Mer), 1997. Etude du risque inondation relatif à la vallée de la Figarella et aux bassins versants littoraux périurbains de Calvi, *Rapport Technique*, 66p.

Boeri and Gauthier, 1994. *Etude historique des catastrophes naturelles en Corse, 1994*, SEMA/DIREN, 69p.

Bouttier, A.; Estienne, J.; Leynaud, G.; Pertus, J.P., and Tiphine, J., 1991. Rapport au ministère de l'environnement concernant l'extraction de granulats dans le lit mineur et le lit majeur de certains cours d'eau (Dordogne, Garonne, Loire, Adour, Durance), 35p.

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

Bravard, J.-P.; Amoros, C.; Pautou, G.; Bornette, G.; Bournaud, M.; Creuzé des Chatelliers, M.; Gibert, J.; Peiry, J.-L.; Perrin, J.-F., and Tachet, H., 1997. River incision in South-East France: morphological phenomena and ecological effects. *Regulated Rivers: Research and Management,* 13, 1–16.

Bravard, J.P.; Kondolf, G.M., and Piégay, H., 1999. Environmental effects of river incision and remedial strategies, *in* Simon, A. and Darby, S. Incised River Channels. New York: Wiley, pp. 303–341.

Bravard, J.P.; Landon, N.; Peiry, J.L., and Piégay, H., in press. Managing erosion and bedload transport on geomorphological basis at the watershed and river scale, Southeastern France. *Geomorphology.*

Brownlie, W.R. and Taylor, B.D., 1981. *Sediment management for southern California mountains, coastal plain and shorline. Part C. Coastal sediment delivery by major rivers in southern California.* Report, 17-C. Environmental Quality Lab., California Institute of Technology, Pasadena.

Carling, P.A., 1981. Armoured versus paved gravel beds. In proceedings of the American Society of Civil Engineers. *Journal of Hydraulics Division,* 106, 1939–1940.

Comhaire, 1988. L'érosion des plages. Exemples sur les côtes de Ligurie et de Corse, 1988. *Mémoire de licence en sciences géographiques,* Université de Liège, 212p.

Dambre, J.L., 1996. Les extractions de matériaux dans le lit mineur et le lit majeur de la Loire et de ses affluents. *La Houille blanche,* 6–7, 108–113.

Defranceschi, J., 1983. Recherches sur la nature de la répartition de la propriété foncière en Corse de la fin de l'ancien régime jusqu'au XIX^{ème} siècle. Doctorat d'histoire. Université Paris 1, Tome II., Paris, 451p.

Dietrich, W.E.; Kirchner, J.W.; Ikeda, H., and Iseya, F., 1989. Sediment supply and development of coarse surface layer in gravel bedded rivers. *Nature,* 340, 215–217.

Dolan, R.; Fenster, M., and Holme, S., 1991. Temporal analysis of shoreline recession and accretion, *Journal of Coastal Research,*, 7, 723–744.

Durand, P., 1999. Cinématique d'un littoral sableux à partir de photographie aériennes et de cartes topographiques. Exemple du littoral d'Argelès-Plage à Saint-Cyprien (Roussillon, France). *Géomorphologie,* 2, 155–166.

Erskine, W.D., 1988. Environmental impacts of sand and gravel extraction on river systems. *The Brisbane River,* 295–303.

Farnole, P., 1996. Aménagement et protection de la plage de Calvi, Tome 1, Rapport d'étude, ERAMM, 63p.

Frihy, O.E.; Fanos, M.A.; Khafagy, A.A., and komar, P.D., 1991. Patterns of nearshore sediment transport along the Nile delta, Egypt. *Coastal Engineering,* 15, 409–429.

Garde, R.J.; Al-Shaikh-Aali, K., and Diette, S., 1977. Armouring process in degrading streams. Proceedings of the ASCE, *Journal of Hydraulics Division,* 103, 1091–1095.

Girel, J., 1986. Télédétection et cartographie à grande échelle de la végétation alluviale: exemple de la basse plaine de l'Ain. *In*: Roux, A.L. (ed.), *Recherches interdisciplinaires sur les écosystèmes de la basse plaine de l'Ain (France): potentialités évolutives et gestion.* Grenoble, pp. 45–73.

Gordon, N.D.; MacMahon, T.A., and Finlayson, B.L., 1992. *Stream hydrology, an introduction for ecologists.* Chichester, 526p.

Grove J. 1988. *The Little Ice Age.* London; Methuen, 498p.

Guillen, J., and Palanques, A., 1992. A Sediment dynamics and hydrodynamics in the lower course of a river higly regulated by dams: the Ebro river. *Sedimentology,* 39, 567–579.

Inman, D.L., 1985. Budget of sand in southern California; river discharge vs cliff erosion. *In*: J. Macgrath (ed.), *California's battered coast, proceedings from a conference on coastal erosion,* California Coastal Commission, pp. 10–15.

Innocenti, L. and Pranzini, E., 1993. Geomorphological evolution and sedimentology of the Ombrone river delta, Italy. *Journal of Coastal Research,* 9, 481–493.

Jimenez, J.A. and Sanchez-Arcilla, A., 1993. Medium-term coastal response at the Ebro delta, Spain. *Marine Geology,* 114, 105–118.

Kellerhals, R. and Bray, D.I., 1971. Sampling procedures for coarse fluvial sediments. Journal of the hydraulics division. 8, 1165–1177.

Komar, P.D., 1996. The budget of littoral sediments, concepts and applications. *Shore & Beach,* 19–26.

Komura, S. and Simons, D.B., 1967. River bed degradation below dams. Proceedings of the American Society of Civil Engineering, *Journal of Hydraulic Division,* 93, 1–14.

Kondolf, G.M., 1994. Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning,* 28, 225–243.

Kondolf, G.M., 1997. Hungry Water: effects of dams and gravel mining on river channels. *Environmental Management,* 21(4), 533–551.

Landon, N., 1996. L'évolution du profil en long des affluents du

Rhône moyen: du constat aux principes de gestion. *Revue de Géographie de Lyon*, 71(4), 363–376.

Landon, N.; Piegay, H., and Bravard, J.P., 1998. The Drôme River incision (France): from assessment to management. *Landscape and Urban Planning*, 43, 119–131.

Larinier, M., 1980. Effets mésologiques des extractions de granulats dans le lit mineur des cours d'eau. *Coll. FAO*, CECPI., Vichy, 192–211.

Leopold, L.B. and Wolman, M.G., 1957. River channel patterns; braided, meandering and straight. *U.S. Geol. Survey Prof. Paper 282-b*, pp. 39–85.

Lewin, J., 1977. Channel Pattern Changes. *In*: K.J. Gregory, (*ed.*), *River Channel Changes*. pp. 167–184.

Liebault, F.; Clément, P.; Piégay, H., and Landon, N., in press. Assessment of bedload supply potentiality from the tributary watersheds of a degraded river: the Drôme (France). *Journal of Arctic and Alpine Research*.

Loye-Pilot, M.D. and Pasquier, C., 1994. Les pluies et crues exceptionnelles de la toussaint 1993 en Corse,—Compte rendu des 23 ème journées de l'hydraulique. *Congrés de la société hydrotechnique de france* (Nîmes, France), 14–16 Septembre 1994, pp. 207–213.

Masselink, G., 1992. Longshore variation of grain size distribution along the coast of the Rhône delta, Southern France: a test of the "Mc Laren Model" *Journal of Coastal Research*, 8, 286–291.

Molinillo, M.; Lasanta, T., and Garcia-Ruiz, J.M., 1997. Managing mountainous degraded landscapes after farmland adandonment in the central Spanish Pyrenees. *Environmental Management*, 21(4), 587–598.

Oliveros, C.; Delpont, G.; Desprats, J.-F.; Dutartre, P.; Girault, F., and Hervé, J.Y., 1997. Littoral occidental Corse—Evolution du trait de côte de 1951 à 1996; Etude de 25 plages des Agriates au golfe de Ventilegne; *BRGM—Rapport nx R39480*.

Ozer, A. and Comhaire, A.L., 1988. Apports de la morphométrie des galets à la connaissance du transport littoral—exemples en Sardaigne, Ligurie et Corse, *Bulletin de la société géographique de Liège*, 4–5, 429–440.

Paskoff, R., 1998. *Les littoraux—Impact des aménagements sur leur évolution*, Paris: Glin, 260p.

Pautou, G., 1984. L'organisation des forêts alluviales dans l'axe rhodanien entre Genève et Lyon; comparaison avec d'autres systèmes fluviaux. *Documents de cartographie écologique*, pp. 43–64.

Peaudecerf, P., 1975. Effets des gravières sur le comportement hydrodynamique des nappes d'eau souterraines. *La Houille Blanche*, 2–3, 133–140.

Peiry, J.L., 1987. Channel degradation in the middle Arve river, France. Regulated Rivers. *Research & Management*, 1, 183–188.

Peiry, J.L.; Salvador, P.G., and Nouguier, F., 1994. L'incision des rivières des Alpes du Nord: état de la question. *Revue de Géographie de Lyon*, 69(1), 47–56.

Pellegrini, M.; Perego, S.; Tagliavini, S., and TONI, G., 1979. La situazione morfologica degli alvei dei corsi d'acqua emilianoromagnoli: stato di fatto, cause ed effetti. *Consiglio Nazionale della Ricerca, Conservazione Sulo, Publ. 80*, pp. 169–195.

Piegay, H.; Landon, N.; Bravard, J.P.; Clément, P., and Liébault, F., 1997. Channel incision and potentiality of reversibility, the Drôme river case, France. *Conference on Management of Landscapes Disturbed by Channel Incision*. (20–22 May 1997, Oxford, Mississippi).

Piégay, H. and Peiry, J.L., 1997. Water line profile evolution of an intra-mountain stream and gravel load management: example of the middle Giffre river (Haute-Savoie, France). *Environmental Management*, 21(6), 909–919.

Piegay, H. and Salvador, P.G., 1997. Contemporary floodplain forest evolution along the middle Ubaye river. *Global Ecology and Biogeography Letters*, 6/5, 397–406.

Poulos S.E.; Collins, M., and Evans, G., 1996. Water-sediment fluxes of Greek rivers, southeastern Alpine Europe: annual yields, seasonal variability, delta formation and human impact, *Zeitschrift für Geomorphologie*, 40,2, 243–261.

Quelennec, R.E.; Dominici, R.; Juncy, G., and Rouire, J., 1982. Le delta du Golo (Haute-Corse)—Dynamique sédimentaire du littoral et des bassins-versants associés (Bevinco-Golo-Fium'alto). *Géochimie des sédiments marins—Détermination des zones sensibles à l'érosion*, BRGM, 70p.

Radulescu, M., 1991. *Le littoral sableux du domaine de Pinia—commune de Ghisonaccia—étude préalable à l'aménagement et à la gestion*. CEPREL, 38p.

Richards, K. and Clifford, N., 1991. Fluvial geomorphology: structured beds in gravelly rivers. *Progress in Physical Geography*, 15(4), 407–422.

Tagliavini, S., 1978. Le modificazioni geomorphologiche ed idrogeologiche conseguenti all'attivita estrattiva nella conoide del torrente Enza. Atti del Convegno Attivita estrattiva dei materiali inerti da costruzioni. Effetti sugli ambienti e risorse alternative, 8p.

Tassone, B.L.; Lapointe, F. and Zrymiak, P., 1992. Field procedures for sediment data collection—volume 1—Suspended sediment. Surveys and information systems branch, Ecosystem sciences and evaluation directorate, DRAFT, 38p.