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Sediment budget as evidence of land-use changes in mountainous areas: two stages of evolution

LUC DESCROIX[1], EMMANUELE GAUTIER[2], ANNE LAURE BESNIER[1], OKECHUKWU AMOGU[1], DAVID VIRAMONTES[3] & JOSE LUIS GONZALEZ BARRIOS[4]

1 *IRD-Niamey BP 11 416, Niamey, Niger* and *LTHE, Laboratoire d'étude des Transferts en hydrologie et Environnement, BP 53, F-38041 Grenoble, France*
descroix@ird.ne

2 *Laboratoire de Géographie Physique, Université Paris 8 et CNRS, F-92195 Meudon Cedex, France*

3 *Instituto Mexicano de Tecnología del Agua, P. Cuauhnahuac 8532, 62 550 Jiutepec, Morelos, Mexico*

4 *Centro Nacional de Investigación Disciplinaria en la Relación Agua Suelo Planta Atmósfera, AP 225-3, 35 071, Gomez Palacio, Durango, Mexico*

Abstract Two sediment budgets, for two widely different hydrological settings, have been prepared, compared and analysed to determine altered hydrological conditions resulting from land-use changes, over extended time periods. French alpine rivers are currently undergoing severe channel entrenchment. This has resulted from the accumulated effects of anthropogenic activity and climatic factors. Bridges and dikes are threatened by the entrenchment, which is the consequence of a major decline in hillslope erosion that began toward the end of the 19th century. On the other hand, in the Western Sierra Madre (northern Mexico), river channels have been rising for some decades, and at the same time widening; this is a consequence of severe hillslope erosion, which is both linear and laminar, and mainly due to overgrazing and deforestation. Both cases clearly demonstrate the impact of anthropogenic activities and, to a lesser extent, climate change, on hydrological conditions.

Key words Alps; erosion; land uses; Mexico; overgrazing; sedimentation

INTRODUCTION

Sediment budgets are strongly linked to erosion in the upper areas of a basin; in turn, erosion is strongly affected by variations in land use within a catchment. Thus, variations in land use, as well as climate change, can modify runoff conditions and bedload transport in basins (Gautier, 1992; Descroix & Gautier, 2002).

This study aims to contrast sediment budgets for two widely different areas that encompass markedly different hydrological conditions that, in turn, have engendered widely different problems.

The first case focuses on an alpine region where population has been decreasing since the middle of the 19th century, after a long period (from the 16th to the 19th centuries) characterized by: (a) rising demographic pressure; and (b) substantial climatic change (the Little Ice Age) (Descroix & Mathys, 2003). As such, the southern Alps have undergone major changes in land use that have caused severe soil degradation and changes in hydrological conditions. In turn, these changes have led to

Table 1 Changes in the extent of forested areas, by region.

Department	Total area (km^2)	Forested area (%) 1770–1780	1878	1914	1948	1992	Forested area in 1992 (km^2)
Alpes de Hte Pce	6954	10*	18*	26	31	36	2500
Hautes Alpes	5534	11*	19	27	29	34	1860
Drôme	6560	15**	23**	29	31	43	2800

(origin: Inventaire Forestier National, cadastre 1948, enquête Daubré 1904-1908, enquête Cerruti 1972 ; * = from Miramont, 1998 ; ** = personal estimations).

Table 2 Changes in the extent of vegetative cover in the Tepehuanes-Guanacevi, Mexico, area.

Vegetation pattern	Area 1972 (km^2)	(%)	Area 1992 (km^2)	(%)	Evolution 1972–1992 (%)
Pine dense forest	400	7.4	155	2.9	–62%
Oaks open forest	1228	22.8	915	17.0	–26%
Mountain “savannah”	1417	26.3	1805	33.5	+27%
Pasture	1591	29.5	1614	30.0	+1.5%
No vegetation	758	14.1	905	16.8	+19%

elevated rates of slope erosion, accompanied by elevated sedimentation on flood plains. Starting with the 19th century, land use and population dynamics changed in the region; population declined and an active policy of reforestation accelerated the effects of a spontaneous afforestation (Table 1). These changes led to a substantial decline in hillslope erosion and caused a significant sediment deficit, that has led to severe river bed entrenchment, in almost the whole alpine massif.

The second case focuses on the Western Sierra Madre region of Mexico, where anthropogenic impacts on the environment are very high, despite substantial emigration (substantial numbers of people are moving to the USA, but cattle ranching and silviculture remain). This pattern has led to increasing deforestation and overgrazing, both of which have negatively impacted the vegetative cover and the soil (Table 2). As a result, erosion has become severe and bedload transport has increased. These hydrological changes have caused riverbed widening and rising, increased reservoir siltation, and an increased chance of flooding. These changes have been highlighted in two study areas: the Sonora and Matape catchments (Sonora State) and in the Nazas catchment (Durango State).

State of the art

In the southern European mountains, the actual landscapes, as well as collective memory (ancient documents as well as oral history) have recorded incidents of catastrophic damage due to severe erosion and torrential rains. In pre-alpine and Mediterranean mountains, intense erosion is related to a combination of geological characteristics (marls), the occurrence of high-intensity rain, and demographic pressure which has led to negative environmental impacts resulting from the effects of the rainfall intensity on erodible watersheds (Descroix & Mathys, 2003). The current sedimentary phase, characterized by the entrenchment of rivers, was documented by Peiry *et al*. (1994) in the northern Alps and by Gautier (1992) in the southern ones.

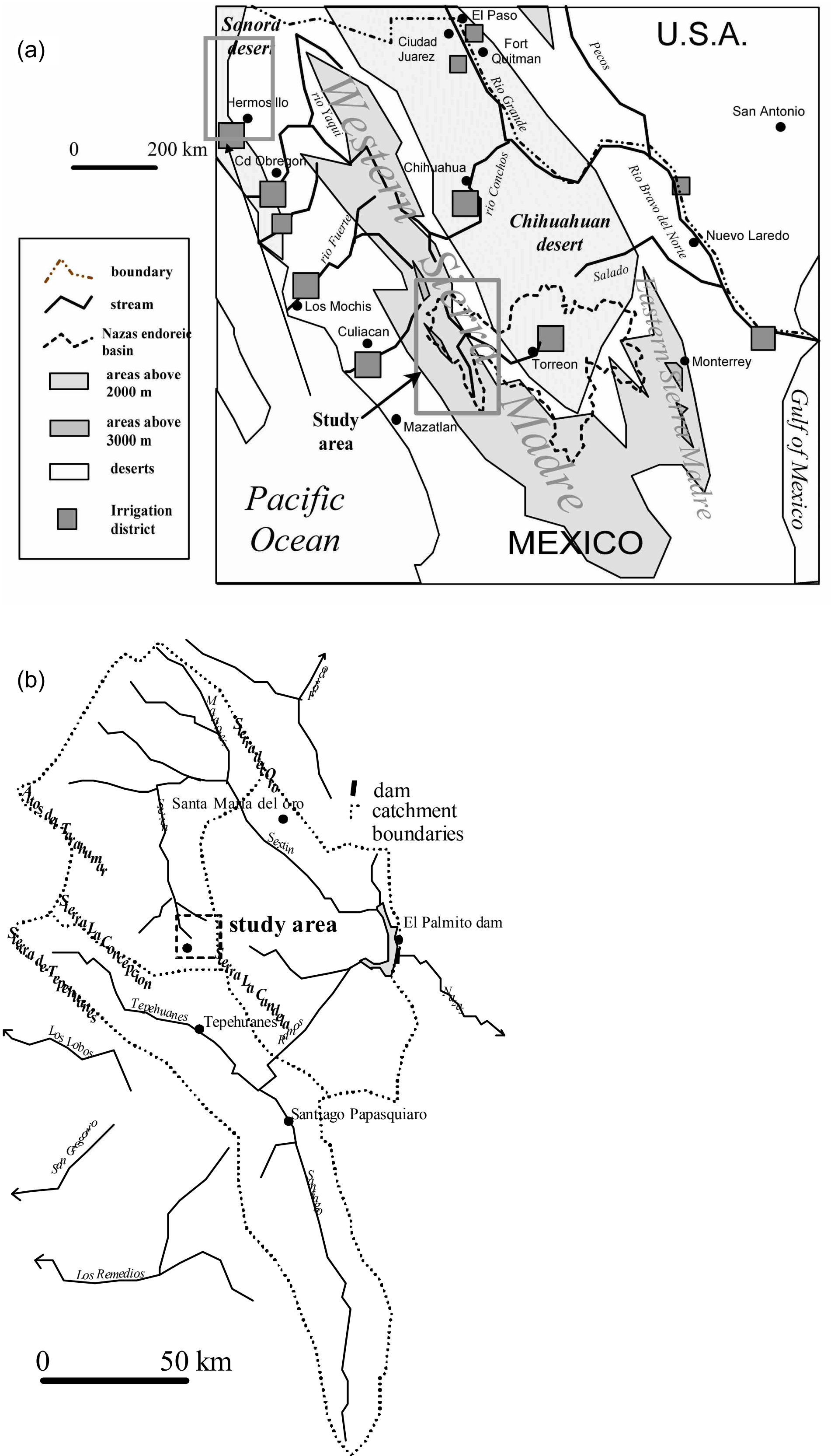

Fig. 1 (a) Location of study areas in northern Mexico: Sonora and Matapé basins in the Northwest, and the Nazas Basin in the centre. (b) The Upper Nazas basin: the study area, and the location of the experimental plots.

In Western Sierra Madre (Fig. 1(a) and 1(b)), changes in surface features have been detected (Descroix *et al*., 2001), and some of their hydrological consequences modelled, at the local scale (Descroix *et al*., 2002). Viramontes *et al* (2003) showed the downstream consequences of these changes, by analysing the evolution of river regimes. They highlighted, among others: (a) an increased lag time in hydrological response to rainfall in basins; (b) the decrease of baseflow (and the increase of flood flows); (c) the reduction of soil water capacity, due to a decline in infiltration as a result of a decrease in the fine particle content of the soil at both local and basin scales; (d) the reduction in soil moisture depletion time; and (e) changes in baseflow indices.

The hydrological regime has been changed significantly due to land-use modifications; it is noteworthy that this land-use evolution could also cause changes in sediment budgets. In the Sierra Madre, these changes could be influenced by the geological context. Thus, the recent development of active erosion is probably due to changes in vegetative cover; this is nearly always caused by anthropogenically induced changes. In developing countries, agricultural or forestry pressure are the main factors leading to vegetative degradation. However, in some cases, a sudden change in geomorphic processes can be related to the crossing of environmental thresholds, without changes in vegetation (Schumm, 1979).

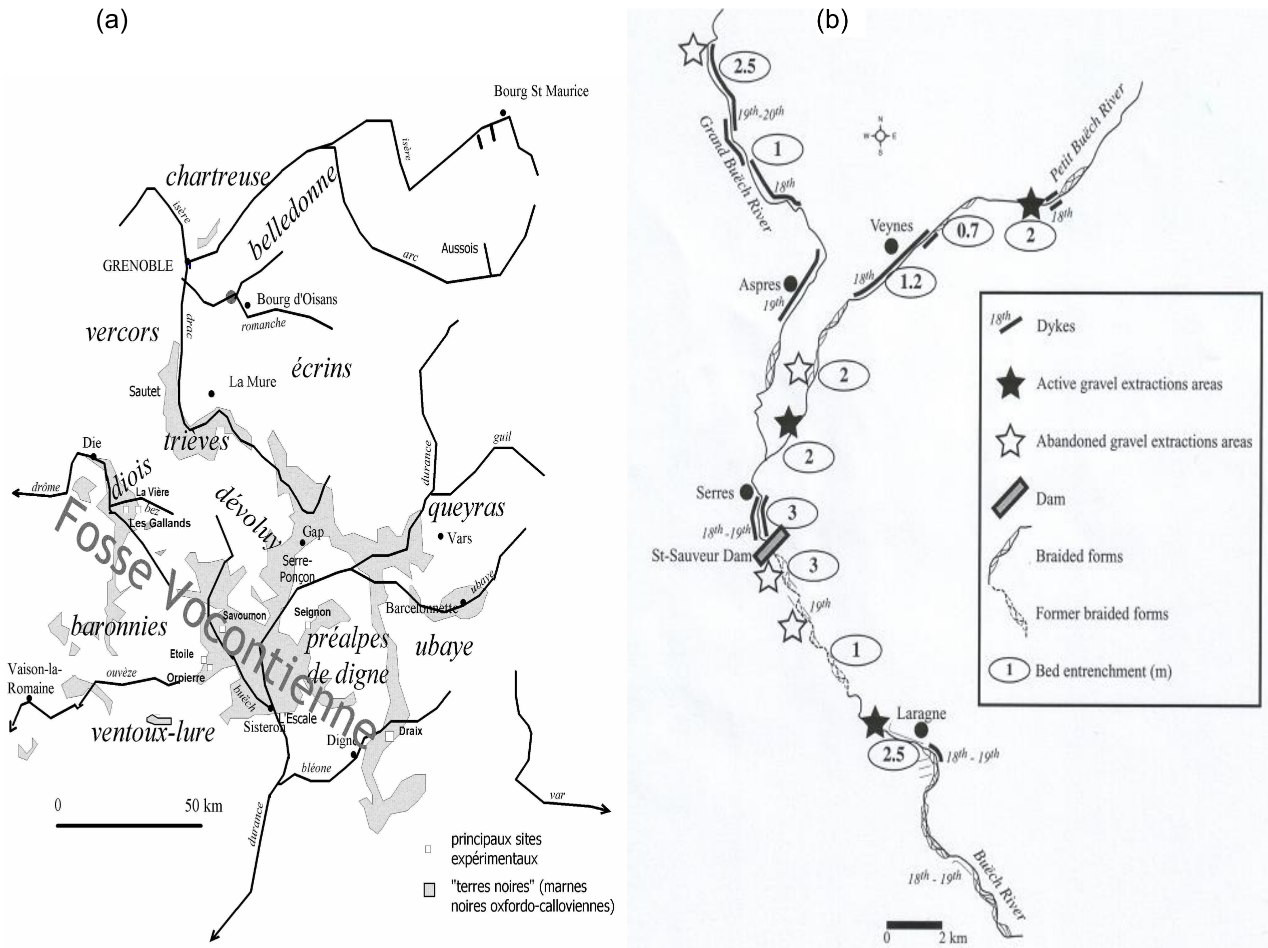

Fig. 2 (a) Location of Buëch valley in the southern French Alps. (b) Degree of riverbed entrenchment in the Buëch River over the three last decades.

Observations and measurements

This study is based on two series of data:

(a) a synthesis of studies and measurements performed during the 1990s:
- in the French Southern Alps (Gautier, 1992; Descroix & Mathys, 2003; Descroix & Gautier, 2002), in seven experimental catchments located in the Diois, Baronnies, and Préalpes de Digne massifs (Fig. 2(a));
- in the Western Sierra Madre (Descroix *et al.*, 2001, 2002, 2004), in five experimental catchments of the upper Rio Nazas basin (Durango State) (Fig. 1(b)).

(b) a series of observations based on photographs and documents :
- a hydrographical study of the Buëch River in the French Alps (Fig. 2(b));
- an aerial survey of the Matapé and Sonora River Basins (Sonora State, México) (Fig. 1(b));

In both regions, cartographic documents and photographs as well as hydrological data, were used to highlight the substantial differences between the alpine and Mexican contexts.

RESULTS: A STRONG DIFFERENCE BETWEEN TWO KINDS OF LAND-USE EVOLUTION

Sediment budget in an overexploited mountain—Mexico

Sheet erosion is the dominant form of soil redistribution in the region (Descroix *et al.*, 2004). The magnitude of the sheet erosion can be estimated based on current soil features (e.g. stoniness, calculation of topsoil removal based on comparisons between vegetated and non-vegetated sites); calculations indicate that, on average, a 10-cm layer of topsoil has been removed from at least 50% of the area under study.

For the purpose of this study, the onset of the current active erosive phase began about 50 years ago (this is somewhat arbitrary as it is based on oral communications from local inhabitants). At that time, there was little or no local agricultural activity, and grazing was limited to a few areas near former large ranches (haciendas). Based on the assumed 50-year-old onset, sheet erosion removed about 2 mm year^{-1}, over half the study area. Even so, a substantial portion of what remained was coarse material. In comparison, gully erosion amounted to 0.006 mm year^{-1}. Hence, the rate of sheet erosion was nearly two orders of magnitude greater than gully erosion. The major cause of increased sheet erosion is overgrazing (Fig. 3).

The estimates of annual erosion have been confirmed, at least at the plot scale (50 m^2). The average value for four plots was 1125 g m^2 year^{-1}; assuming a topsoil mean bulk density of 1.5 (average of all measurement points), this represents a soil loss thickness of about 0.75 mm year^{-1} (average of the four plots) As a result of the substantial quantities of coarse material (31% by volume, 37% by weight), that obviously is not subject to sheet erosion, average annual soil losses are on the order of 1.1 mm year^{-1}. This only represents about half of previous estimates (Descroix, 2004); however, as the current estimate only is applicable to half the study area, both estimates are in reasonable agreement.

Fig. 3 Overgrazed hills in the middle basin of the Rio Sonora (Sonora State, Mexico).

The current estimate of soil loss due to sheet erosion also is consistent with the results from two bathymetric surveys in the El Palmito reservoir (Descroix, 2004). The dam was constructed in 1946. When the total volume of sediment in the reservoir is divided by the total area of the basin, the annual estimate is some 0.5 mm year^{-1}. However, it should be noted that material is not evenly derived from the whole catchment because nearly 20% is covered by forests, and some 35% is savanna (erosion rates are lower in these areas due to the presence of numerous trees). Further, estimates based on reservoir siltation are likely to represent only minimum values because some proportion of the material removed from the hillslopes by sheet erosion collects in depositional zones located between the source and the reservoir. Qualitative support for the presence of elevated levels of erosion in the region also is based on the occurrence of: (a) riverbed widening and rising (Fig. 4); (b) extension and expansion of floodplains; (c) dike and bridge burial, and (d) reservoir siltation. Similar occurrences also have been observed in the Nazas (Durango State) as well as in the Sonora and Matapé basins (Sonora State).

It would appear that overgrazing is one of the most significant factors leading to increased erosion (and sediment yield) in the northern region of Mexico. The upper parts of the catchments are underlain by resistant volcanic rocks; hence, even substantial deforestation does not lead to substantial increases in erosion. On the other hand, the middle sections of the basins, including all regions located between the forests and alluvial plains (generally cultivated) are underlain by tuffs and conglomerates. These rock types are very susceptible to erosion; as these areas are dedicated to grazing, which removes most if not all of the vegetative cover, the middle sections of these catchments are the most important sediment source in northern Mexico (Fig. 3). However, increased erosion as a result of overgrazing, while widespread, has only been ongoing for two or three decades.

Fig. 4 Alluvial material in excess, invading the lower part of a tributary (left edge) of the Rio Matapé (Sonora State, Mexico)

Sediment budget in an abandoned mountain—European alpine areas

In alpine areas, bedload transport has declined considerably since the end of the 19th century. In the past (pre 1900s), in the southern French Alps, two underlying rock types have provided heavy volumes of sediment: black marls (Fig. 2(a)) and rock flour from glacial moraines. It has been estimated that erosion in black marl areas ranged between 7 and 11 mm $year^{-1}$, whereas erosion rates in glacial flour areas ranged between 14 and 18 mm $year^{-1}$. Similar rates also have been observed in unvegetated sections which can represent between 5 and 20% of catchment areas. Currently, the percentage of catchment areas containing bare soil, and their associated erosion rates, has remained approximately the same. However, active reforestation has substantially limited the quantity of sediment reaching river channels because the increased vegetation has isolated the areas that are still subject to erosion and hence, precluded the material from reaching the riverbeds. The impact of the new forest growth also has been enhanced by the spontaneous growth of other types of vegetative cover. Reforestation programs were initiated by the national government (during the second Empire and then during the third Republic) in conjunction with rural engineering projects; however, much of the reforestation was spontaneous, as a result of voluntary population relocation from rural to urban areas accompanied by declining levels of silviculture and grazing.

The changes in the levels of vegetative cover, along with changing population demographics, were also accompanied by substantial infrastructural changes in active stream channels which reduced both the availability as well as the transport of sediments. These changes included: (a) dike construction during the 18th and 19th centuries that led to bank stabilization and reduced erosion; and (b) dam/reservoir construction in the alpine massif (300 alone in the French Alps) that generated a large number of sediment traps. In addition, beginning in the 1950s, although currently illegal, massive sand and gravel mining occurred in active stream beds; these activities further reduced the quantity streambed sediments.

Lastly, the end of the Little Ice Age moderated the local climate, reducing rainfall impact, and as a consequence, erosion. However, in most of the small alpine valleys, where neither gravel extraction nor dam/dike construction took place, river bed entrenchment still occurred. This would seem to demonstrate that catchment reforestation alone would be sufficient to produce a "sediment deficit" sufficient to negatively impact streambed geomorphology (Fig. 5). One of the more interesting features of the alpine system is the issue of "lag" time. It took some decades between the onset of reforestation, and sand and gravel mining, before the onset of detectable impacts (retrenchment) in the active streambeds in the region. This appears to have been due to the length of time required to reduce the amount of sediment in storage in these river channels, and move it from upstream to downstream locations. In the Buëch River basin, the lag time has been estimated as some 30 years in a 100 km^2 basin, and 70 years in a 1000 km^2 one (Gautier, 1992).

Fig. 5 The Buëch River valley immediately downstream from Saint Sauveur Dam (Hautes Alpes, France); the entrenchment of the bed (more than 3 m since 1992) in its own alluvium is detectable on both sides.

CONCLUSION

A substantial reduction in vegetative cover appears to cause rising and widening riverbeds due to increases in erosion and the accompanying increase in fluvial sediment. Inversely, an increase in vegetative cover causes a substantive reduction in erosion, with concomitant riverbed retrenchment. The length of the response times for a particular river basin, to changes in vegetative cover, infrastructural additions, changing population demographics, and other anthropogenic activities, appears to be related to the surface area of the basin. Current overgrazing in Mexico, and in the past in the Alps, exercised a substantive control over sediment supplies in catchments. These observations would support the view that land-use changes, as well as other anthropogenic activities (engineering construction, sand and gravel mining) may well be the most relevant factors in the evolution of riverbeds.

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