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River channel response to short-term human-induced change in landscape connectivity in Andean ecosystems

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Abstract

The drainage basin of the Deleg River (88 km^2), located in the southern Ecuadorian Andes, was studied to assess the geomorphic and hydrologic response of a fluvial system to human-induced environmental change in its contributing area. Historical data on land use, channel morphology and sedimentology were collected, based on a spatial analysis of aerial photographs (1963–1995) and a field survey (2002). Analysis of channel cross-sectional profiles and sedimentological data revealed a major change in morphology and sedimentology of the Deleg River during the past four decades: (i) the active river channel narrowed by over 45%, (ii) the riverbed incised on average by over 1.0 m and (iii) the median grain size of the bed surface decreased from 13.2 cm to 4.7 cm. The spatial pattern of land cover within the Deleg catchment also changed considerably: highly degraded agricultural land in the low-lying areas was abandoned and partially afforested for timber and wood production, whereas secondary upland forest was increasingly cleared for expansion of cropland and pastures. Notwithstanding large changes in the spatial organization of land use within the catchment, the overall land use did not change significantly during the past four decades. This suggests that the response of the Deleg River to land-use change not only depends on the overall land-use change, but also on the spatial pattern of land-use/cover change within the catchment. Although forestation and regeneration of bare gully slopes and floors throughout the catchment only represented a minor part of the total land-use change, these land-use/cover changes had a major impact on the hydrological and sediment connectivity in the landscape.

Keywords: Land-use change; River morphology; River channel change; Sediment connectivity; Aerial photographs; Andes; Ecuador

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1. Introduction

During the last decades, land use and land cover in the Andes region have changed drastically due to a growing population and a changing economy (Vanacker et al., 2003a; Wiegers et al., 1999). These alterations in land use/cover on the hillslopes often have important effects on spatial and temporal dynamics of hillslope hydrology and sediment production, transport and delivery to upper reaches of streams (Braud et al., 2001; Dunne et al., 1991; Krishnaswamy et al., 2001; Rey, 2003). Hillslopes and upstream reaches are closely linked to river channels downstream, and changes in biophysical and hydrological processes on the hillslopes are likely to induce major changes in river channel morphology, and water and sediment transport downstream (Harvey, 1991; Kondolf et al., 2002; Walling, 1983).

The change in channel morphology and fluvial sediment transport as a response to up-stream human-induced environmental changes has recently been investigated in various environments (Chen et al., 2001; Fryirs and Brierley, 1999; Garcia-Ruiz et al., 1997; Kondolf et al., 2002; Liebault et al., 2002). These studies documented historical modifications in catchment characteristics, as well as their effects on sediment supply to the fluvial system and river channel morphology. In most studies, the relationship between land-use dynamics in the catchment and fluvial morphology and sedimentology was analysed using a lumped statistical approach, whereby river channel dynamics is related to changes in overall land use (e.g. the percentage forest cover).

Recent investigations by Harvey (1991, 2001), Hooke (2003) and Vanacker et al. (2003b) have shown that sediment production, transport and delivery to river channels downstream is not only dependent on the overall catchment physiography, but also on the spatial organization and the internal connectivity of various physiographic units. Few, if any, of these previous studies on fluvial response have considered the impact of changes in the spatial organization of land use on river channel morphology and sedimentology.

The main objective of this paper is, therefore, to assess the response of an upland fluvial system in a tropical mountain environment to human-induced changes in land-use patterns. The drainage basin of the Deleg River (88 km^2), located in the southern Ecuadorian Andes, was taken as a case study to highlight the geomorphic and hydrologic response of an upland fluvial system to rapid human-induced land-use change in the upstream area. The specific objectives of this study are: (i) to identify historical change in channel morphology and sedimentology using aerial photographs and field surveys, (ii) to quantify historical change in land use, landscape fragmentation and connectivity using aerial photographs, and (iii) to investigate to what extent historical changes in the spatial organization and connectivity of land units within the catchment have affected river channel morphology and fluvial transport of sediment.

2. Study area

The Deleg River drains an 88 km^2 catchment in the southern part of the Ecuadorian Andes, flowing 20 km southeast and then 8.5 km eastward to its confluence with the Burgay River, about 20 km northeast of the city of Cuenca (Fig. 1). Altitudes range from 2320 m a.s.l. at the catchment outlet to 3800 m a.s.l. at the water divide. Catchment slopes are generally very steep, ranging from 15% to 70%. Locally steeper slopes (ca. 90%) are found in the deeply dissected river valleys. Only in the lower part of the Deleg catchment slopes are much gentler (1–15%). Land use is dominated by cropland and pastures (ca. 35% of the catchment area) and so-called wastelands (ca. 24%) interspersed with Eucalyptus plantations, followed by rangeland (ca. 15%), native forest (ca. 11%) and high alpine paramo vegetation (ca. 9%). Wastelands are highly degraded areas, located on steep slopes, which are used for grazing. The vegetation cover is variable, but is generally sparse (<20%) and consists mainly of shrubs and some grasses. Pastures are also used for grazing, but they have a nearly 100% vegetation cover consisting of grasses.

The Deleg basin is located in the Inter-Andean depression and has a complex geological structure. The basin is primarily underlain by sedimentary, volcanic and glacial sediments of the Upper Miocene to the Present (Coltorti and Ollier, 2000). The lower and middle part of the basin is made up of continental sedimentary rocks including alluvial fans as well as fluvial, lacustrine and pyroclastic deposits of the Upper Miocene (Noblet et al., 1988). The upper part

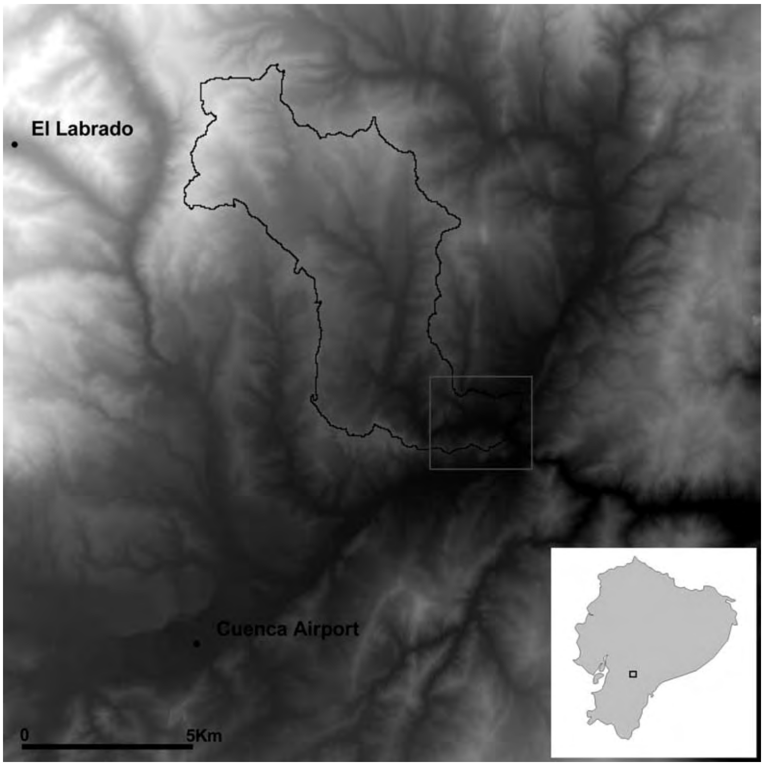

Fig. 1. Topographic setting of the Deleg catchment, with indication of the lower reach of the Deleg River.

of the basin consists of volcanic deposits of Middle Pliocene to Lower Pleistocene age, except for a small outcrop of glacial sediments in the upper Northwest.

The region is characterized by a bimodal rainfall regime with two distinct wet and dry seasons. Mean annual precipitation increases strongly with elevation, and ranges from 827 mm at the station of Cuenca Airport (2516 m a.s.1.) to 1272 mm at the station of El Labrado (3280 m a.s.1.). The mean annual discharge of the Deleg at its confluence with the Burgay River is estimated at ca. 2.17 $m^3 s^{-1}$ for the period 1970–1980, with low discharges from December to January and July to August and high discharges from April to May and October to November (INECEL, 1982). The course of the Deleg River (28 km in length) can be divided into two morphologically distinct segments: (i) the upper and middle reach (ca. 20 km), and (ii) the lower reach (ca. 8 km, Fig. 1). In the upper and middle part of the Deleg catchment, the topography is mountainous with deeply dissected drainage lines. In its upper and middle reaches, the Deleg River has developed a steep gorge in a narrow valley. Here, the river channel is characterized by a sinusoidal pattern (sinuosity equals 1.52) for most of its length, and has an average channel gradient of 8% and a narrow channel bed (ca. 3–4 m for the middle reach and ca. 1–2 m for the upper reach as measured on the 1995 aerial photographs). The lower reach of the Deleg crosses the hilly lower part of the catchment in an eastward direction, and has a wide, relatively flat valley floor formed by old alluvial deposits (Fig. 4A,B). Here, the river channel now has an overall meandering pattern, which alternates with small braided sections (sinuosity equals 1.69). The lower reach has a relatively wide channel bed (16 m measured on the 1995 aerial photographs), and the average channel gradient is 1.5%.

3. Materials and methods

A historical analysis of channel morphology and sedimentology was undertaken on the lower reach of the Deleg River. The lower reach traverses a broad, open valley and spreads out over a large area (Fig. 1), which facilitates the observation of spatial and temporal changes in channel morphology and sedimentology. Historical changes in land use in the catchment area draining to the lower river reach were mapped using sets of aerial photographs taken in 1963 and 1995 and were validated during a field survey in 2002. Additional topographic, climatic and socio-economic data were collected to explain observed land-use/cover changes and spatial changes in river morphology and sediment transport.

3.1. Aerial photoanalysis

A spatially consistent database detailing historical changes in land use and river channel morphology was developed in a GIS (ILWIS 3.0). Data were derived from sets of aerial photographs taken in 1963 (scale of ca. 1:50,000) and 1995 (scale of ca. 1:35,000). First, the aerial photographs were converted into a raster graphic format by scanning the photographs at 1000 dots per inch (dpi) using an A3 flat scanner. The scanning resolution of 1000 dpi yields pixel dimensions of between ca. 1.27 m and 0.89 m on the ground for the photographs at scales of 1:50,000 and 1:35,000, respectively. Second, the aerial photographs were geometrically corrected for systematic displacements (e.g. lens distortion, earth curvature, refraction), and orthorectified for scale variations and image displacement resulting from terrain relief and camera tilt. The mathematical relationship between the image (X,Y) and the ground coordinate system (X,Y,Z) was established using a Digital Elevation Model (DEM) and a set of Ground Control Points (GCPs).

These GCPs were collected by measuring the geographic position of at least 15 reference points by GPS (Trimble Geo-Explorer) in the field. Prolonged GPS measurements of two second-order geodetic points showed a mean horizontal accuracy of 2 to 3 m. The orthorectified photographs were then resampled to create digital orthophotos, which have a uniform scale throughout so that distances, angles and areas could be measured and mapped on-screen. The horizontal positional accuracy of all orthorectified imagery was consistent and always better than 5 m.

The digital orthophotos of 1963 and 1995 were interpreted and classified by on-screen digitising (Fig. 2). All classifications were validated during an extensive field campaign in 2002. Seven major land-use categories were distinguished in the catchment area: (1) water; (2) high alpine paramo vegetation; (3) native forest consisting of semi-evergreen upland forest (i.e. Polylepis forest), upper montane rain forest and montane shrub vegetation; (4) plantation forest consisting mainly of Eucalyptus species; (5) agriculture (i.e. cropland and rangeland); (6) wasteland with a very poor vegetation cover; and

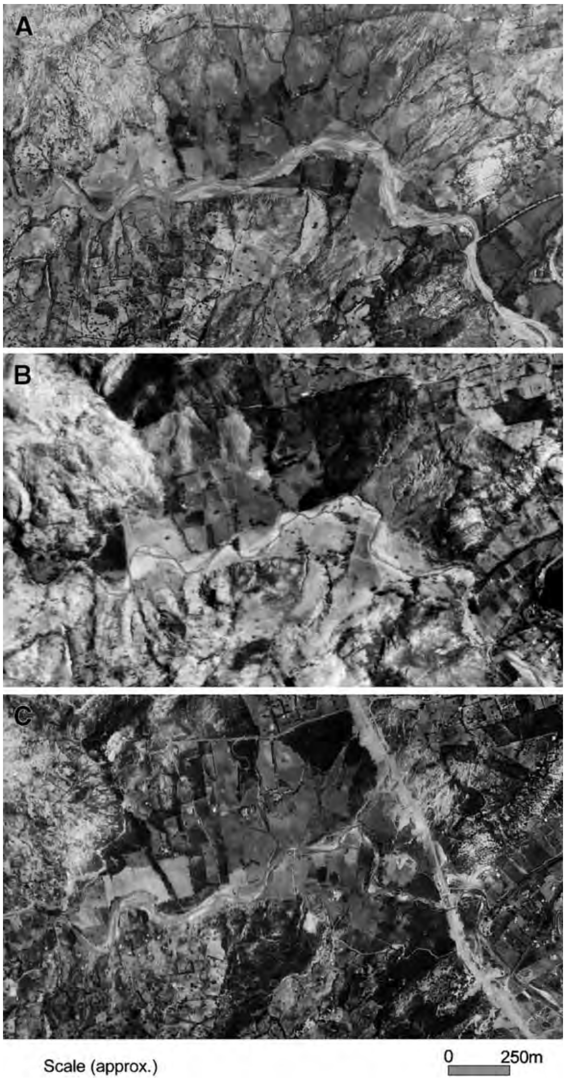

Fig. 2. Aerial photographs of 1963 (A), 1980 (B) and 1995 (C) of the lower reach of the Deleg River.

(7) urban areas. The stream channel morphology of the lower reach of the Deleg River was characterized by digitising the channel planform on the orthophotos of 1963 and 1995. The edges of the active channel were traced based on clearly identifiable changes in vegetation type and density. Stream channel boundaries and active central and lateral gravel bar areas were delineated on the aerial photographs and separately digitised. As old channels and gravel bars are still clearly visible in the field, the maps of the river morphology were cross-checked using GPS. Additionally, this information was confronted with interviews of local residents.

3.2. Site surveys and measurements

Channel geometry was analysed on the basis of cross-sectional surveys of the valley bottom morphology. The surveys provide complementary information on change in channel morphology, which also allows a crosscheck of the data derived from the aerial photographs. Along the 8-km lower reach of the Deleg River, 11 cross-sections of the valley floor were surveyed. The location of each cross-section was measured with GPS, and located on the orthophotos (Fig. 3). Channel cross-sections were established perpendicular to the direction of the flow, and extended laterally 2 m beyond the limits of the valley bottom. At each cross-section, the main morphological features across the river valley were identified, and their location and relative elevation were surveyed (Fig. 3). Some geomorphological features (old gravel bars, terraces, etc.) could be dated approximately using archival evidence from interviews with local older people.

Variations in size of channel deposits may reveal changes in the flow regime of the Deleg River through time. Therefore, in addition to the analysis of channel geometry, a quantitative analysis of river channel sedimentology was conducted following Kondolf (1997). The granulometric analysis for the time period represented on the orthophoto of 1963 was based on pebble counts at vertical cross-sections through old gravel bars, which were identified and located in the field based on the orthophotos of 1963: in total, the D_{50} and D_{90} of the gravel present in the terrace

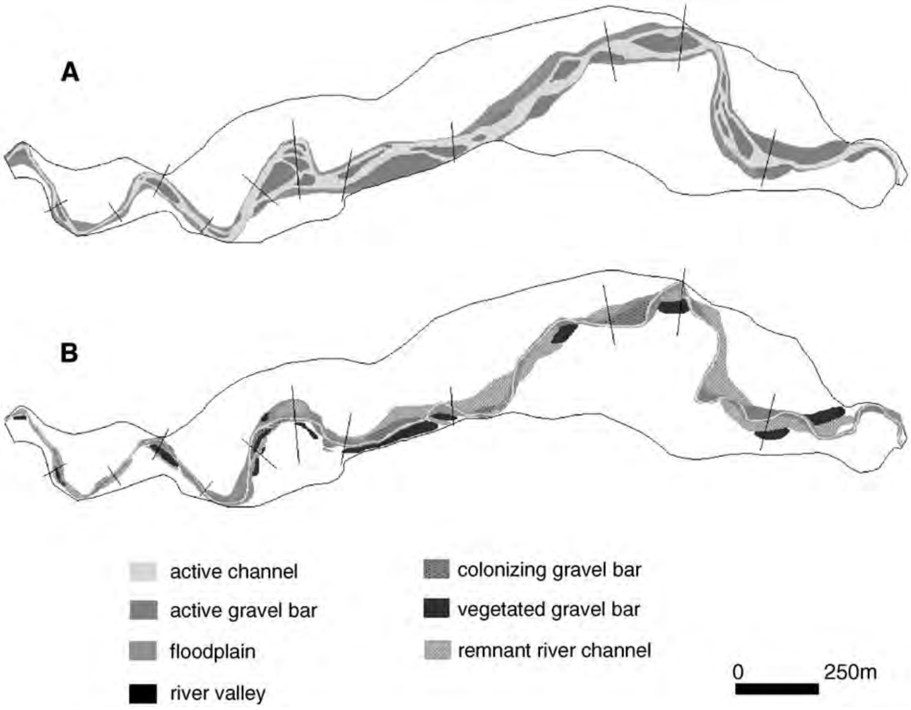

Fig. 3. Map of channel trajectory in 1963 (A) and 1995 (B) with indication of the transects.

deposits were measured at 40 locations (Fig. 5). The mean grain size of these gravel bars was compared with that of the actual bed material below the armour layer, which was determined by conducting pebble counts at ca. 100 locations along the active river channel.

3.3. Complementary data

In order to analyse the effect of additional variables potentially influencing sediment and water transport within the Deleg catchment, data related to topography, drainage, rainfall and human population dynamics were also collected. Altitude, slope and geomorphic characteristics of the Deleg catchment were derived from a 30 m resolution digital elevation model (DEM). This DEM was created by gridding and interpolating vectorised contour lines with a 20 m interval derived from the 1:10,000-scale topographical map (INECEL, 1982). The drainage network was automatically generated from the DEM data using the multiple-flow algorithm of Quinn et al. (1991). Rainfall records were analysed to examine possible changes in temporal or spatial rainfall patterns during the study period (1963–1995), which could have influenced the catchment hydrology. As no historical records of daily rainfall data are available for the area, time series of monthly rainfall data for two long-running rainfall stations (i.e. Cuenca Airport, 2516 m a.s.l. and El Labrado, 3280 m a.s.l.) were studied to detect potential trends in precipitation patterns. The rainfall stations of Cuenca Airport and El Labrado are representative for, respectively, the lower and middle part, and the upper part of the Deleg catchment (Fig. 1).

4. Historical channel changes (1963–1995/2002)

4.1. Change in channel geometry

Air photoanalysis and field surveys showed that the lower reach of the Deleg River underwent significant changes in channel geometry between 1963 and 1995/2002 (Figs. 2 and 3, Table 1). The river morphology evolved from its braided pattern, with multiple channels of shallow water and large active gravel bar areas in 1963, to a more sinuous, single-thread and slightly entrenched meandering channel in 1995/2002.

Throughout the 8 km lower reach, a general trend of channel narrowing was observed (Fig. 3). The change could be quantified based on the orthophotos of 1963 and 1995. Changes in channel width along the 8 km reach vary between − 14 and − 58 m or − 49% and − 88% (Table 1). Correlation analysis indicates that both the absolute and relative change in channel width are a function of the channel width of 1963 ($R^2 = 0.96$ and 0.58, respectively).

The cross-sectional surveys of the valley morphology indicate that the change in channel width is associated with channel incision (Fig. 4B). The present river channel is entrenched in its former riverbed, which now forms a low terrace close to the present channel. The rate of channel incision was estimated from the differences in level between the formerly active channel identified on the orthophotos of 1963 and the present river channel. Incision rates of between 23 and 44 mm year^{-1} (i.e. between 0.9 and 1.7 m) were evident throughout the 8 km reach. The recent channel incision caused large portions of formerly active braided channels and bars to be disconnected from the main river channel, and subsequently abandoned, colonized and stabilized by vegetation (Fig. 4B).

Table 1
Change in channel geometry and bankfull discharge

	1	2	3	4	5	6	7	8	9	10	11
Width_{1963} (m)	32	35	39	25	29.5	28.5	29	70	38	52.5	71.0
Width_{2002} (m)	9.5	9.5	15	10.5	15	14	11.5	16	15	6.5	13
Change in $\text{width}_{63\text{-}02}$ (%)	− 70	− 73	− 62	− 58	− 49	− 51	− 60	− 77	− 61	− 88	− 82
$\text{Incision}_{63\text{-}02}$ (m)	− 0.9	− 1.0	− 0.9	− 0.9	− 1.2	− 1.5	− 1.4	− 1.7	− 1.3	− 1.2	− 1.0
$Q_{\text{b\_1963}}$ ($m^3 s^{-1}$)	66	65	66	65	65	74	64	75	70	80	87
$Q_{\text{b\_2002}}$ ($m^3 s^{-1}$)	21	18	18	19	18	19	19	20	21	22	22
Change in $Q_{\text{b\_63-02}}$ (%)	− 68	− 73	− 72	− 70	− 72	− 74	− 70	− 73	− 71	− 72	− 74

The columns represent the 11 cross-sections of the 8-km lower reach of the Deleg River.

Fig. 4. Photographs of lower part of the Deleg catchment (A), the lower river reach (B) and gully systems stabilized with Eucalyptus trees (C).

Bankfull discharges (Q_b, m^3 s^{-1}) were estimated for both 1963 and 2002 using the Manning's formula (Leopold et al., 1964):

$$Q_b = \left(\frac{R^{2/3}S^{1/2}}{n}\right)A$$

where R=hydraulic radius (m), S=water surface slope (m m^{-1}), A=channel cross-sectional area (m^2) and n=Manning's resistance coefficient at bankfull stage (Table 1). The Manning's n value for bankfull discharge was estimated at 0.049, based on roughness coefficients computed for the adjacent Machangara river system by Alvarez et al. (1994). Calculated discharges are an estimate only. Nevertheless, they reflect past and present flow conditions in the lower reach of the Deleg River. The relative differences between the estimates obtained for 1963 and 2002 indicate that the bankfull discharge of the Deleg river has been significantly reduced.

4.2. Change in channel sedimentology

Pebble counting was used to assess changes in the size distribution of the bed material, which may reflect changes in flow conditions in the lower reach of the Deleg River. Fig. 5 shows the particle size distribution of the channel deposits of 1963 and 2002. The bed material of the contemporary channel is characterized by a geometric mean particle size of 47 mm and a standard deviation of 21 mm, whereas the old channel deposits have a mean particle size of 132 mm and a standard deviation of 35 mm (Fig. 5). The bed material critical shear stress (τ_c) for the mean particle size was estimated for both 1963 and 2002 using the Shield criterion approach,

$$\tau_c = \rho_w g R_{cr} S = \theta_c g D_{50}(\rho_s - \rho_w)$$

where ρ_s=density of the sediment (kg m^{-3}), ρ_w=density of water (kg m^{-3}), g=gravitational acceleration (m s^{-1}), R_{cr}=critical hydraulic radius for initiation of motion (m), S=water surface slope (m m^{-1}), θ_c=dimensionless critical shear which was estimated at 0.056 for gravel bed channels, and D=particle diameter (m) that τ_c can move. Based on the estimates of the critical shear stress, the critical hydraulic radius for initiation of motion (m) was derived: the critical hydraulic radius decreased from ca. 1.04 m in 1963 to ca. 0.37 m in 2002. Thus, the overall decreasing trend of the mean particle size of the bed material also suggests that the critical flow depth for motion of sediment and, thus, peak discharges decreased.

5. Land-use change (1963–1995)

Over 32 years, ca. 14% of the total catchment area has undergone major changes in land use, which are

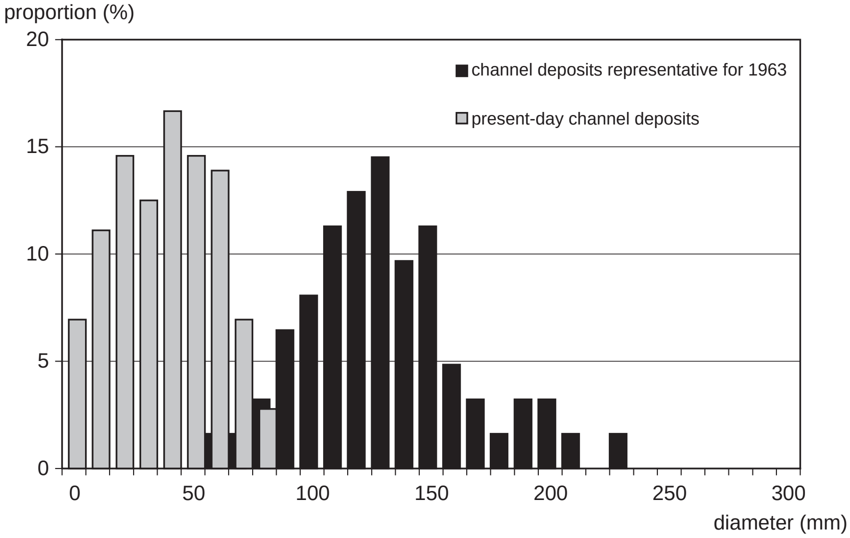

Fig. 5. Grain size distribution of channel deposits of 1963 and those of the present-day channel. (Note that *y*-axis is rescaled to 100%, i.e. total number of measurements).

mainly driven by rapidly changing socio-economic and demographic conditions. Increasing population pressure in the fertile low-lying valleys, where the population was traditionally concentrated, has stimulated (i) the intensification of the farming system, and (ii) the upward movement of the agricultural frontier. Approximately 319 ha (i.e. 7%) of the arable land was taken out of crop production, and was used as urban land (c. 8 ha) and commercial forest plantations (c. 310 ha, Fig. 6). Secondary native forest was increasingly cleared and replaced by agriculture, and the area of native forests reduced by 331 ha (i.e. 26% of the total forested area in 1962) over a period of 32 years. Despite these important changes, the overall forest cover of the catchment did not change significantly: the deforestation of native forest in the upper area was almost completely compensated by the reforestation with *Eucalyptus* trees along gullies, streams and parcels boundaries, and on degraded soils in the low-lying areas. Also, no major net change in agriculture

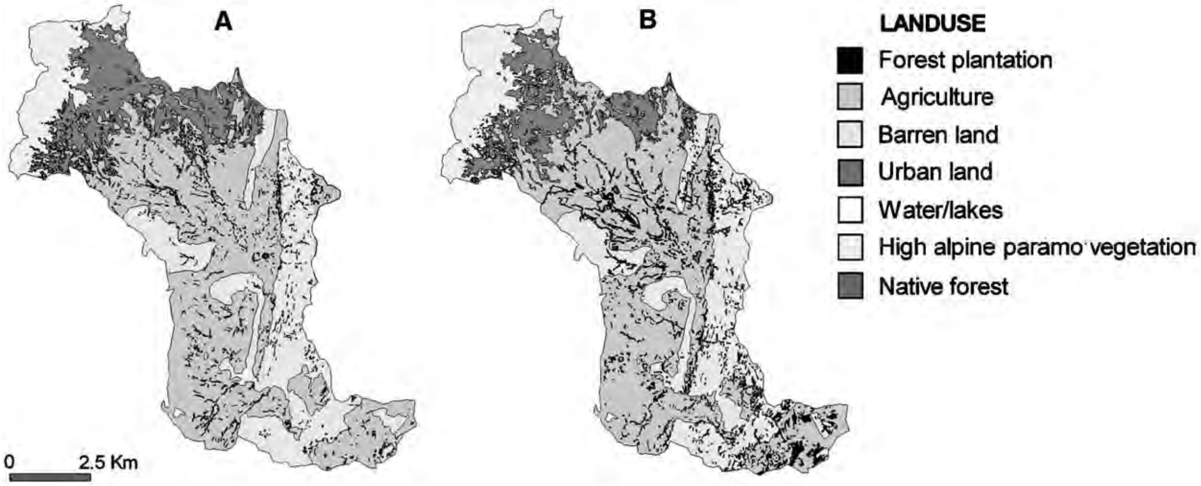

Fig. 6. Land-use maps of 1963 (A) and 1995 (B) based on aerial photoanalysis.

or wasteland areas could be observed, despite large internal spatial dynamics (Table 2, Fig. 6).

Besides changes in overall land use, important changes occurred within certain landscape units. The expansion and intensification of the agrarian land use were not sufficient to cope with the rapidly increasing population pressure in the area. The fragmentation of small landholdings due to rapid demographic growth continuously reduced the efficiency of small farms, and severely limited agricultural productivity. These constraints on agricultural productivity forced the peasant population into national and international migration to supplement the marginal agricultural earnings. The village of Deleg, located in the central part of the catchment, experienced significant outbound migration since the 1980s, which is evidenced by its negative migration index (− 1.5 1%; INEC, 1991). However, this official migration index (calculated as the number of immigrants minus emigrants accepted per year, divided by the total population number) is known to be largely underestimated, as most of the outbound migration is illegal. Therefore, the proportion of females in the total working age population (18–55 years) probably provides more realistic data on the extent of the migration: ca. 71% of the working age population of Deleg now consists of females (INEC, 1991). This overrepresentation of females in the working age population clearly points to a massive outbound migration of males. The massive outbound migration of the 1980s and 1990s had clear impacts on the agrarian land use. Crazing pressure on the wastelands in the lower part of the catchment have significantly decreased (Fig. 2). This has had positive effects on the regeneration of grasses, shrubs and small bushes during the 1990s (Fig. 4C). The bush density, as measured on the orthophotos of 1963 and 1995 for randomly selected transects within the degraded areas, increased from 4.2% in 1963 to 5.8% in 1995. Vegetation increase was most noticeable in drainage lines: these were often actively eroding channels in 1963 while in 1995 most of them were stabilized by vegetation (mainly shrubs).

Table 2
Land-use change during the period 1963–1995

Land-use categories	1963	1995	Change (1963–1995)	
	km^2	km^2	km^2	%
Forest plantation	1.8	4.9	3.1	(+172)
Agriculture	43.4	44.3	0.9	(+2%)
Barren land (very low vegetated)	22.0	21.2	− 0.8	(− 4%)
Urban land	<0.1	0.1	0.1	(+414%)
Water/lakes	0.1	0.1	0.0	
High alpine paramo vegetation	7.8	7.9	0.1	(+1%)
Native forests	12.6	9.2	− 3.4	(− 27%)

6. Potential factors controlling river morphology and sedimentology

The cross-sectional and sedimentological data clearly indicate that the Deleg River underwent major changes in discharge and sediment supply during the past four decades. Any understanding of these changes should be based on the identification of the causes of these changes. In this case, three potential factors controlling short-term change in river morphology and sedimentology can be proposed: (i) the 1993 flood, triggered by the Josefina landslide, (ii) natural short-term variations in the rainfall regime, and (iii) human-induced land-use/cover change.

In 1993, the Josefina landslide event (estimated to be 30 million m^3) blocked the Paute River in Southern Ecuador, and flooded the valley 10 km upstream of the dam. As a consequence of this event, a small section of the river valley in the lower part of the Deleg catchment was also temporarily flooded. It is known that the high water carried willow seeds, which germinated along the margins of the low flow channels. The forestation of the riverbanks will probably have accelerated the stabilization of the river channel since 1993. However, from the aerial photographs of 1980, it is clear that the observed changes in river morphology already started well before 1980, as the river pattern of 1980 is very similar to the sinuous, single-thread and slightly entrenched meandering channel of 1995/2002 (Fig. 2). Thus, it can be stated with certainty that the river narrowing and deepening is not principally linked to the flood event of 1993.

As no historical gauging data are available for the southern Ecuadorian Andes, time-series of rainfall data (1930–1990) were analysed to assess potential hydrological changes in the catchment. Time-series of monthly precipitation data from the stations of Cuenca Airport (1930–1990) and El Labrado (1963–1990) were collected, and anomalies relative to the mean of the time period 1964–1990 were calculated to detect general long-term trends in precipitation. Fig. 7 shows the percent anomalies in monthly precipitation relative to the mean monthly precipitation of the period 1964–1990 for both rainfall stations. There is clearly a large variability of monthly precipitation for both rainfall stations over the last decades. However, no general trend in monthly precipitation can be observed.

Given that the monthly rainfall pattern did not undergo major changes during the past decades, changes in land-use/cover are most probably the major factors controlling change in river morphology and sedimentology. Although the net amount of change between the major land-use systems (i.e. forest, agriculture and barren land) was relatively small, the spatial distribution, fragmentation and vegetation cover of the land-use systems changed significantly (Fig. 6). The land reforms together with the demographic boom of the 1960s and 1970s induced major shifts in the spatial land-use pattern. The prevailing land-use systems moved upwards, and large landholdings were increasingly redistributed and fragmented in favor of the landless and smallholders. The landscape pattern principally changed from large-scale homogeneous land units managed by a few large-sized farms towards a patchy landscape fragmented into many middle- and small-sized landholdings (Figs. 4A,C and 6). Two landscape parameters were selected to quantify the change in landscape pattern: (i) the mean perimeter-to-area ratio (km km^{-2}), and (ii) the mean fragmentation index, which is calculated as follows (Monmonier, 1974):

$$F = \left(\sum_{i=1}^{m} \left(\frac{n-1}{c-1} \right) \Big/ m \right)$$

where n = number of different classes present in the kernel of 5 by 5 pixels, c = number of cells considered

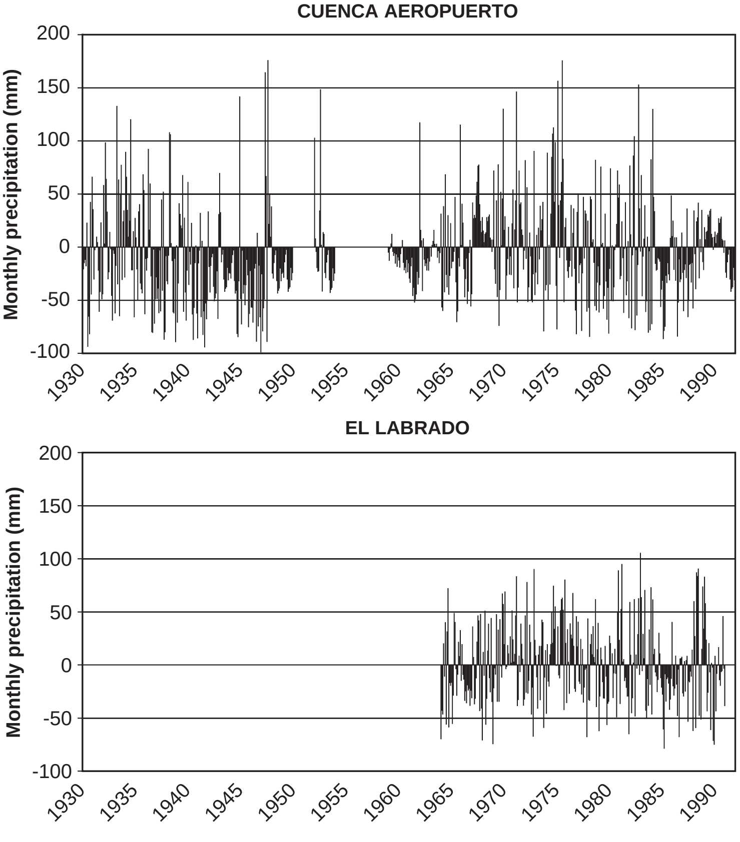

Fig. 7. Rainfall anomalies relative to the mean of the time period 1964–1990 for the station of (A) Cuenca Airport and (B) El Labrado.

Table 3
Change in landscape parameters during the period 1963–1995

	Fragmentation		Perimeter-to-area ratio (km km^{-2})	
	1963	1995	1963	1995
Overall	0.0187	0.0189	15.7	20.3
Forest plantation	0.0404	0.0404	157.2	105.9
Agriculture	0.0124	0.0125	12.8	14.7
Barren land (very low vegetated)	0.0071	0.0109	7.7	12.5
Urban land	0.0292	0.0228	48.5	32.5
Water/lakes	0.0194	0.0203	26.6	28.2
High alpine paramo vegetation	0.0069	0.0066	9.0	8.5
Native forests	0.0154	0.0187	23.5	29.2

in the 5 by 5 pixels kernel and m = number of pixels in the image. The mean fragmentation index for the entire catchment did not change, despite a clear increase in the overall patch perimeter-to-area ratio, which generally increased from 15.7 km km^{-2} in 1963 to 20.3 km km^{-2} in 1995 (Table 3). The former result is probably an artefact due to the definition of rather broad land-use systems (e.g. agriculture), which means that shifts in landscape pattern within these large land-use systems (e.g. parcellization) are undetectable using the fragmentation index. There are large differences in the change measured by the landscape metrics between the various land-use systems. Generally, barren land and native forest are characterized by a strong increase in fragmentation; whereas the fragmentation remained more or less constant for other land uses.

In addition to the increasing land fragmentation in the middle and upper areas, the decreasing human population pressure in the low-lying areas due to outbound migration during the 1980s and 1990s had clear impacts on the overall vegetation cover of the barren land. As the land pressure on these marginal areas significantly decreased, the natural vegetation cover could slowly regenerate. At present, the vegetation cover of the barren land is characterized by grasses, herbs and shrubs on the hillslopes, and shrubs and bushes in the formerly active gully systems.

It is clear that the spatial pattern of the observed land-use/over change had major effects on the hydrological fluxes in the catchment, and influenced the river morphology and sedimentology. Particularly, the spatial pattern of land-use/cover change on low-lying barren land played a key role in understanding the change in hydrological fluxes and sediment connectivity. These marginal, degraded areas were formerly characterized by a very low vegetation cover, and produced large volumes of surface runoff and sediment during rainfall events. As these degraded areas are densely rilled and gullied, the runoff and sediment produced on the barren land was quickly transferred to the river network causing high peak flows and sediment fluxes in the river system. First, the overall increased landscape fragmentation resulted in the creation of many vegetative barriers within and between different land units. In the highly degraded areas, the overall density of bushes (measured as the ratio of the area covered by bushes to the total area) increased from 4% in 1963 to 7% in 1995. These barriers retard and reduce surface runoff by promoting water retention and re-infiltration, and stimulate the deposition of eroded sediment. Second, the overall increased vegetation cover of the degraded land due to diminishing land pressure increased the surface infiltration, and reduced the surface runoff (Fig. 8). This was clearly observed in the catchment of the Machangara River, where the abandonment of marginal, degraded areas induced major change in the water and sediment balance of the barren land. In the Machangara catchment, evapotranspiration and infiltration of degraded land increased due to the development of a protective vegetative and dead leaf

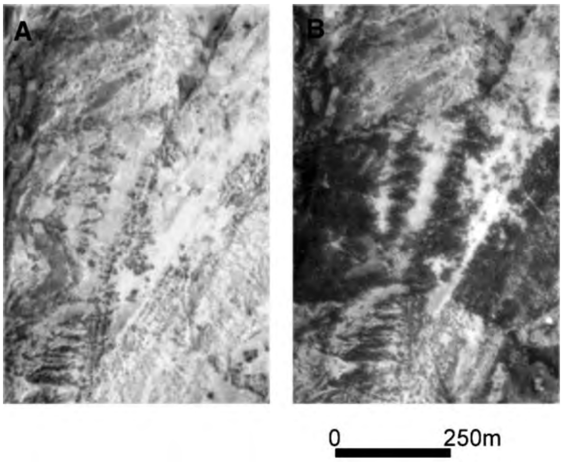

Fig. 8. Change in landscape connectivity in highly degraded areas between 1963 (A) and 1995 (B). In 1963 (A), the degraded area is barren, and highly dissected due to intense gully erosion. It is clear from (B), that the vegetation cover in the degraded areas is higher in 1995. Particularly in the gully floors, the vegetation has regenerated.

cover, which likely resulted in a decrease of surface runoff and sediment detachment and transport. As a consequence of the reduced runoff volume, formerly active gully systems became stabilized and started to function as vegetation barriers for water and sediment (Vanacker et al., 2003b). Our analyses indicate that similar land-use/over change and hydrological processes occurred in the Deleg catchment (Fig. 4C).

7. Conclusions

The spatial analysis of sequential aerial photographs (1963–1995) clearly shows that the morphology of the lower reach of the Deleg River changed significantly. The river pattern evolved from its braided form with multiple shallow branches to form a more sinusoidal, single-thread and slightly entrenched channel. Channel cross-sectional surveys confirm the hypothesis of a narrowing and entrenching river channel, and pebble counts indicate that the sediment transport in the river channel decreased. Historical rainfall data were collected to assess potential trends in the rainfall pattern, but no clear changes in the monthly rainfall amount could be detected. Thus, the historical land-use/cover change that occurred in the Deleg catchment is the main driving factor for changes in water and sediment transport from the hillslopes to the river system.

Land-use change analysis indicates that overall changes in the surface area of the major land-use systems were relatively small. However, the spatial distribution, fragmentation and vegetation cover of the various land-use classes changed significantly during the last decades. The land reforms, together with the demographic boom of the 1960s and 1970s, resulted in a strong redistribution and fragmentation of the land units, whereas, later on, the decreasing human population pressure during the 1980s and 1990s, due to outbound migration, stimulated the abandonment and subsequent regeneration of the vegetation cover on the marginal, barren land. The overall increase in vegetation cover of the wastelands was relatively limited, but important changes took place in critical landscape zones. The stabilization of active gullies by vegetation would have reduced the transfer of water and sediment from the gully catchment to the river as well as sediment production within the gully systems.

Particularly, the land-use/cover dynamics of the degraded land were a key factor in the dynamics of the river system. These formerly barren lands produced large surface runoff volumes and sediment during rainfall events, which were quickly and effectively transported to the river system through a dense network of actively eroding rills and gullies. The increased vegetation cover on these degraded lands promoted the stabilization of formerly active gully systems, which started to function as barriers for water and sediment transport. These observations indicate that the response of the Deleg River to land-use/cover change mainly depends on the changes in spatial organization and connectivity of various land cover types within the catchment, and not so much on the overall amount of land-use/cover change.

The effect of land-use/cover change on the hydrological and sediment connectivity has often been overlooked when interpreting river channel changes, as former studies have tended to analyse the observed river channel changes in relation to catchment dynamics using a lumped statistical approach. Our study shows how relatively small land-use/cover changes within the catchment have had a clear and detectable impact on the river channel morphology and the fluvial transport of sediment. The change in river morphology and sedimentology was not primarily related to the overall land-use/cover change, but to the change in spatial organization and connectivity of land-use systems within the catchment, which largely affected the routing of water and sediment fluxes from the hillslopes to the river systems. These findings have important consequences for integrated catchment management, as the reduction of sediment transport on the hillslopes and sediment transfer to the river system is a key issue in the optimisation of the use of runoff water as a natural resource (drinking water, energy production). Our results clearly demonstrate that the efficiency of erosion control measures on sediment production and delivery can largely be improved when these measures are spatially organized in a strategic way such that the hydrological and sediment connectivity are mostly reduced. This spatial organization of erosion control measures reduces implementation costs, and optimises the existing land use/cover in the catchment.

Tropical mountain areas are generally considered to be fragile ecosystems undergoing rapid deterioration at present (e.g. Lal, 2001; Nyssen et al., 2004). Although this may generally be true, our study shows that the situation is sometimes more complex: while deforestation in the upper part of the Deleg catchment has continued, the recovery of vegetation in the lower part of the catchment has led to slope stabilization and a reduction of river activity, much similar to what has been observed in reforested mountain areas in Europe (Kondolf et al., 2002; Liebault et al., 2002).

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