A conceptual geomorphological model for the development of a Mediterranean river basin under neotectonic stress (Buonamico basin, Calabria, Italy)

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Abstract The Buonamico River basin in Calabria, southern Italy is part of the active collision belt between the African and European plates. It drains to the southeast of the Aspromonte Mountains of the Calabrian Massif of basement rocks, from an elevation of 1956 m down to the Ionian Sea. During Pleistocene uplift of the Aspromonte, rivers incised intensively, causing massive amounts of erosion on the corresponding valley slopes. From long-term investigations of active present day fluvial processes, a conceptual model of the interrelationships between mass movements and debris flows created on the slopes, and their effects on the development of the local river systems is proposed. Amongst the main controls of the development of the valley basin are the availability of erodible material from the slopes, and a river system which is capable of adjusting to both violent tectonic impacts and extremely variable situations of sediment input from the adjacent slopes.

INTRODUCTION AND REGIONAL SETTING

Study area

The Buanamico River basin is situated in the Aspromonte Mountains of Calabria, southern Italy (Fig. 1), which are part of the active collision belt between the African and European plates. There is still considerable speculation as to their tectonic setting (cf. Ibekken & Schleyer, 1991, p.11) with theories ranging from inter- or intra plate deformation, to subduction or a deep-seated shear zone. The Aspromonte Mountains are part of the Calabro-Peloritan arc, a region with the highest tectonic activity in Europe. During Pleistocene uplift, the Aspromonte Mountains were raised by 1100-1300 m. Rivers still incise intensively, causing massive amounts of erosion in the valleys and on their slopes. Lembke (1931) first attempted to describe the tectonics and geomorphology of the region.

The Buonamico basin has an area of 139 km^2, of which approximately 75% lies in the Aspromonte mountains. Monte Alto forms the highest point with an altitude of 1955 m. The basin is underlain by schists (54%), and gneiss (13%) whilst the border and foreland zone consists of sandstone 17%, siltstone, conglomerate 3% and argillite 3%.

The topography was digitized using a 250 × 250 m grid system (Ibekken & Schleyer, 1991). The differentiation of altitude and gradient as a function of distance from the river mouth is displayed in Fig. 2. Maximum differences in altitude of up to 1000 m occur in the middle part of the longitudinal profile which coincides with steep slopes of about 30°. Erosion rates were calculated using the approach of Görler & Uchdorf (1980). The topography before uplift and the volume subsequently eroded from the valleys were determined. In Fig. 2 the maximum erosion rates occur within the valley reach that lies half way between the Mont Alto and the Ionian Sea. Total amounts of erosion can thus be calculated but not the short term relationship between slope development and the river bed. The short term functional relationship (Ahnert, 1970) between denudation, relief and uplift will be investigated in the area of the Buonamico basin, a small Mediterranean basin under neotectonic stress.

Aims

The aims of the study are to combine the processes of slope and river development under unusual neotectonic conditions within a conceptual model. Long-term steady state conditions cannot exist on the river bed because of episodic delivery of material from the slopes by mass movement and the many decades required to transport this input through the fluvial system into the sea. The different time-scales over which slope development and river development proceeds are investigated. Magnitude-frequency distributions of slope-and-river associated events differ substantially (Ergenzinger, 1988). The formulation of

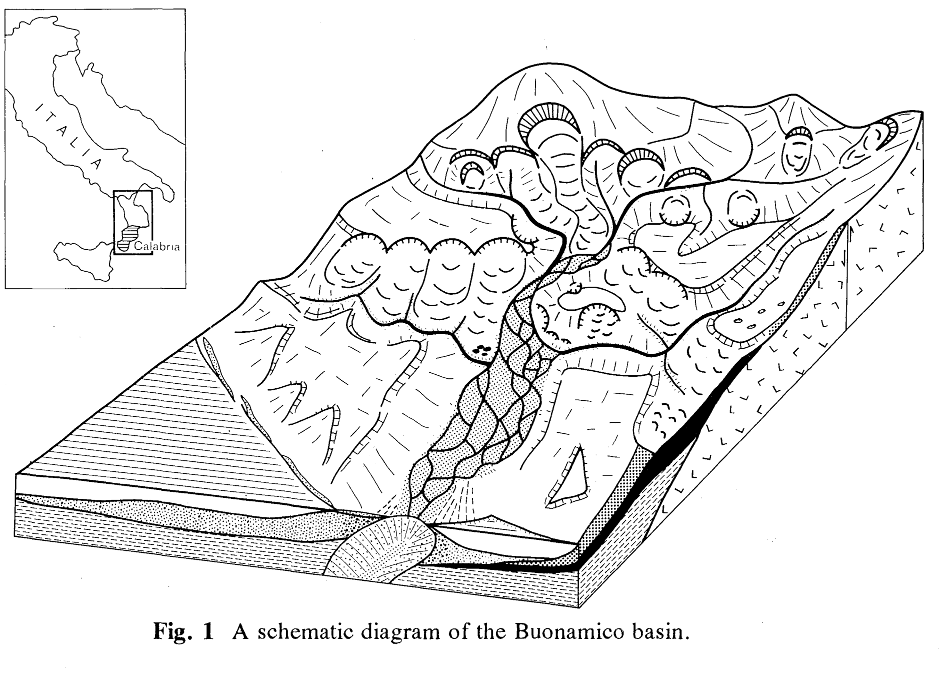

Fig. 1 A schematic diagram of the Buonamico basin.

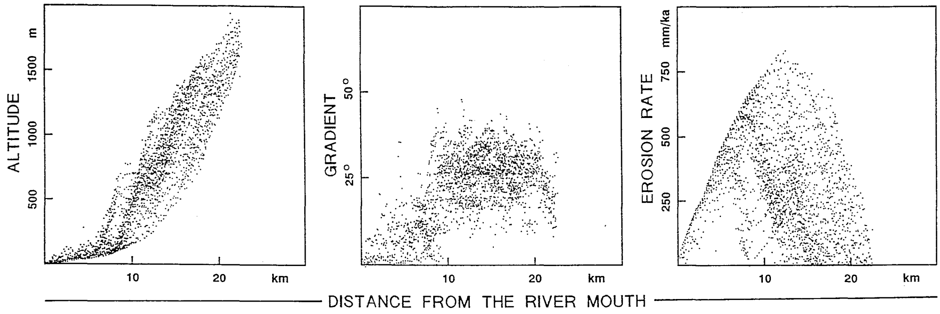

Fig. 2 Distribution of altitude, gradient and erosion rates with the distance from the mouth of the Buonamico River (points refer to a grid system of 250 × 250 m).

special feedback mechanisms controlling the interaction of the system is therefore necessary for the model.

Methodology

The distribution and volumes of mass movements were determined by aerial photo interpretation for 1941, 1955 and 1973. River cross profiles were measured annually between 1972 and 1980 and again in 1986. The longitudinal river profile was surveyed in 1980 which allowed comparisons with the topographic maps of the Instituto Geografico Militare at 1:10 000.

On 4 January 1973, a lake was created by the Costantino landslide in the middle reaches of the Buonamico mountain valley. Since this event, the bed load transported from this part of the basin and deposited in the lake delta has been evaluated on a year by year basis. In the period between the winters of 1978 and 1980, hydrology and solid material budgets of the lake drainage basin were measured on an event basis.

Precipitation was measured from 1927 to 1972 at the Santuario di Polsi in the uppermost part of the catchment. On the Ionian side of the Aspromonte there is no other comparable climatological station in the higher parts of the mountain. A ground penetrating shallow seismic technique was used in order to determine the Holocene fluvial infill in the lower valley and the depth of the weathered mantle on the slopes.

Discussion

Slope development in the Buonamico basin is dominated by mass movements. Only a small part of the uppermost catchment is without active mass movements. The distribution of the weathering mantle is very uneven and location specific. Resistant rocks are to be found only along the divides and on the lower parts of the slopes. As was shown by Mouton in Italpros (1986) there can be up to 40 m of disintegrated material on the middle parts of the slopes (Fig. 3). This material is cohesionless, without interstitial fill, whereas the scree close to the surface consists of a silty matrix with unevenly distributed stones. For this type of scree, layers of stratified stones are typical due to the influence of running water, yet in all other respects they are similar to periglacial screes.

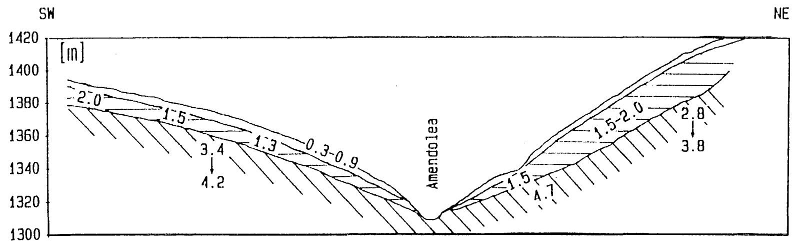

Fig. 3 Depths and travel times (km^{-1}) across the Amendolea River along a 2 km section.

Deep disintegration has most probably been caused by earthquake activity which is also of fundamental importance in the initiation of mass movements. The disintegration mantle can be found wherever there are traces of former mass movements, but it is uncertain whether this mantle was created by, or was a prerequisite for, the mass movements. Regardless of this question, it is clear that the entire slope dynamics are controlled by the availability of disintegrated slope material.

In contrast to the slope dynamics associated with mass movements, the impact of material eroded by fluvial processes is rather insignificant and will therefore not be treated in this paper.

According to Terzaghi (1960), landslides are controlled by both internal and external factors. External causes, resulting in an increase in shear stress, are created by loading (e.g. due to material loading or the storage of water), earthquake shocks or undercutting of slopes. Internal causes lead to a decrease in shear resistance by pore water pressure or to a decrease in cohesion of the slope material.

During the last half century all large mass movements in the Buonamico basin occurred in response to extreme precipitation events. Caloiero & Mercuri (1980) summarized the influence of large precipitation events occurring from 1921 to 1970, whilst Cotecchia *et al.* (1969) described the impact of the extreme earthquake of 1783 on the local geomorphology. If all precipitation events with more than 100 mm are added together for an entire winter season, this sum correlates well with the occurrence of mass movements. Thus whenever more than 1200 mm of accumulated precipitation occur, there is a very high probability of the occurrence of a landslide (Fig. 4(a)).

The size and volume of recent landslides were determined by aerial photo

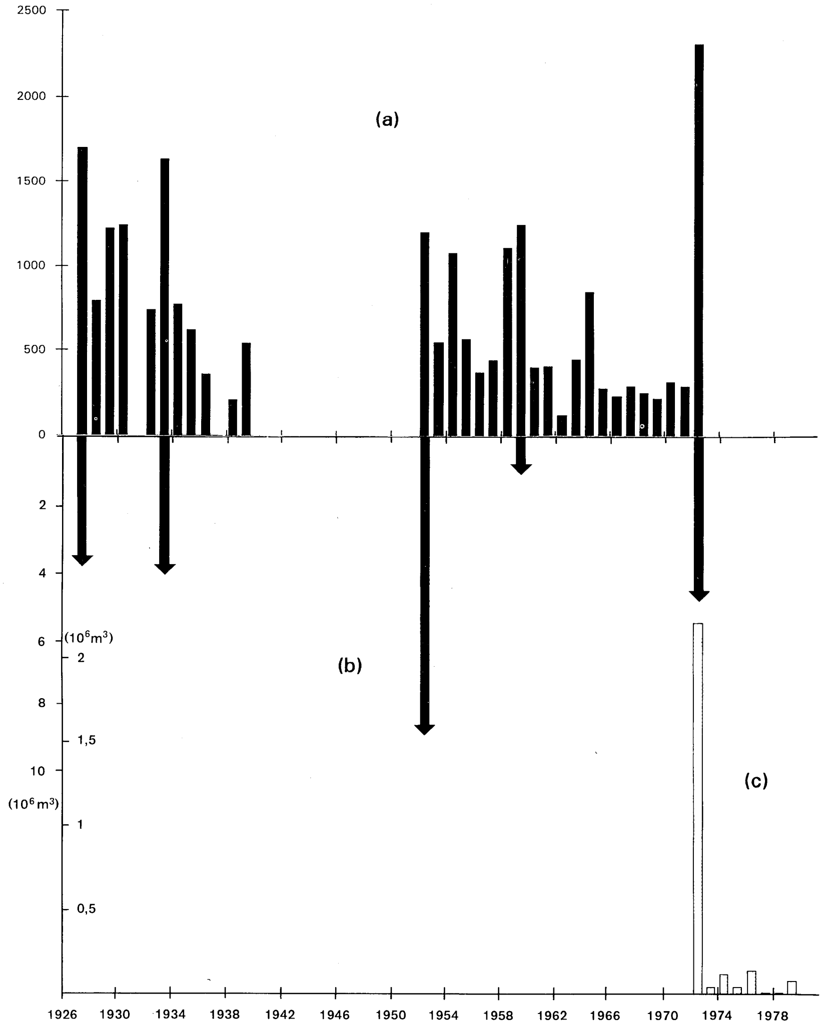

Fig. 4 (a) Annual extreme precipitation: summary of all precipitation events above 100 mm day^{-1}. Volume of landslide material transported (b) to the valley bottom, and (c) by the Buonamico.

interpretation (Fig. 5). The resulting total volumes associated with different time periods are shown in Table 1. The sediment input from mass movements into the river has been estimated as 20% of the total volume. This is a conservative estimate.

The availability of material for transport by the river is governed by the input of material from mass movements. These inputs are of low frequency and high magnitude. In years between the mass movements with low flood discharges (i.e. under high frequency conditions), the transported volumes are of the order of 10^3 or 10^4 m^3. Figure 6 attempts to demonstrate the distribution of magnitude/frequency for the slope processes (cf. Wolman & Miller, 1960). Magnitudes and frequencies of the related fluvial transport will be discussed later.

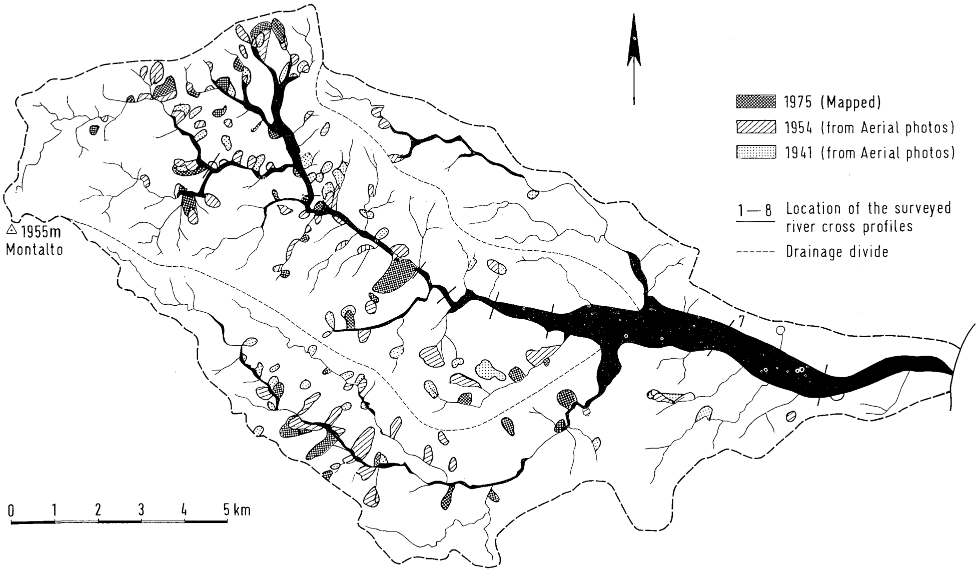

Fig. 5 Recent landslides in the Buonamico basin.

River bed development is a reaction to solid material transport and episodic winter floods associated with high precipitation. Since the river is rather steep, suspended load is more or less directly transported into the Ionian Sea, whereas bed load is transmitted step by step through the braided system of the Buonamico foreland. The long term geological development of the river bed can be represented from comparisons for the period 1955-1980 (Fig. 7). More than 4 million m^3 of sediment were deposited during this time interval. The Costantino landslide in 1953 caused a large input of coarse material at km 14. Below the landslide the narrow mountain valley was filled with 50 m of sediment. The largest amount of material is nevertheless not to be found in the mountain areas, but in the foreland where average river widths increase up to 800 m (km 7). Between 1955 and 1980 erosion occurred close to the sea where the Buonamico was dammed and widths were reduced to 200 m. Even though seven active winter seasons had passed after the landslide, the former river bed conditions could not be restored. The input of more than 2 million m^3 of material from the Costantino landslide by fluvial erosion created a far too great

Table 1 Landslide occurrence in the Buonamico basin.

Aerial photo from	Landslides from	Landslide area (km^2)	Volume ($\times 10^6$ m^3)	Input into the river ($\times 10^6$ m^3)
1941	1933	2.1	21	4
1955	1951	4.3	43	9
1973	1958, 1973	3.0	30	6
last 50 years		9.4	94	19

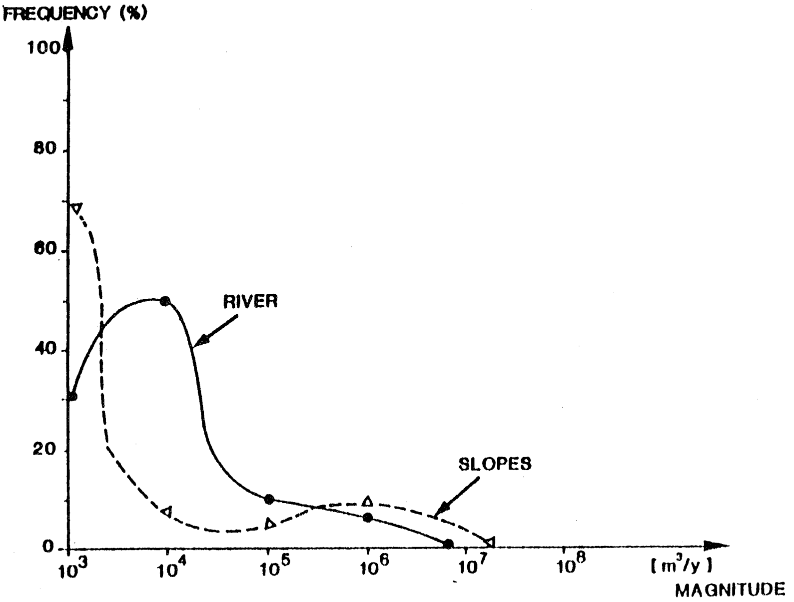

Fig. 6 Magnitude/frequency diagram for slope and river events in the Buonamico basin.

disturbance of the river bed conditions. The development of the river bed was surveyed on a yearly basis with a set of cross profiles. Between 1972 and 1986, only part of the input of the extreme event of 1973/1973 was eroded. (Fig. 8).

The magnitude/frequency distribution for fluvial transport differs markedly from that of the slopes (Fig. 6). Based on extrapolation of the amount

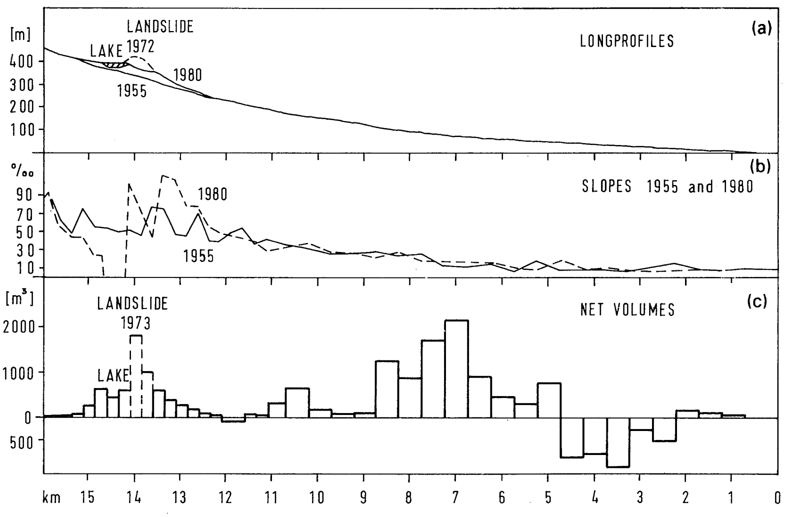

Fig. 7 The Buonamico long profile: (a) comparison and (b) gradient of the long profiles of 1955 and 1980; (c) net volume differences between 1955 and 1980.

of solid material deposited in the Lago Costantino above the landslide, sediment transport over the last two decades averaged about 10 000 m^3 per year. The maximum amount of solid material transported in 1972/1973 is estimated at between 5-9 million m^3. The recovery time required to erode and transport material from the last major landslide is at least 20-25 years. This is comparable to the observations of Wolman & Gerson (1978) on semiarid rivers.

As Scheidegger (1991, p.110) stated, endogenic uplift must be compensated by downhill mass movement, but large amounts of mass movement require the evacuation of the infilled material by running water. Although extreme precipitation events cause both extreme landslides and floods, the amount of material transported into the valley bottom according to our observations is several times greater than the transport capacity of the related floods.

The river system therefore requires several decades before it can re-establish the former level of the river bed. During this time interval, the lower slopes along the infilled parts of the valley are protected against undercutting. Only where there is a valley zone with intense incision is there a high probability for new landslides created by extreme precipitation. Thus infilling and undercutting form the main feedback mechanisms between the slope and river bed dynamics.

CONCLUSIONS

The development of slopes and fluvial systems proceeds over different time-scales and with different magnitudes and frequencies in the Buonamico basin. Especially under conditions of neotectonic uplift, the coupling of the two systems is dictated by the longitudinal development of the river profile. The development of the longitudinal profile is affected by both the tectonic uplift

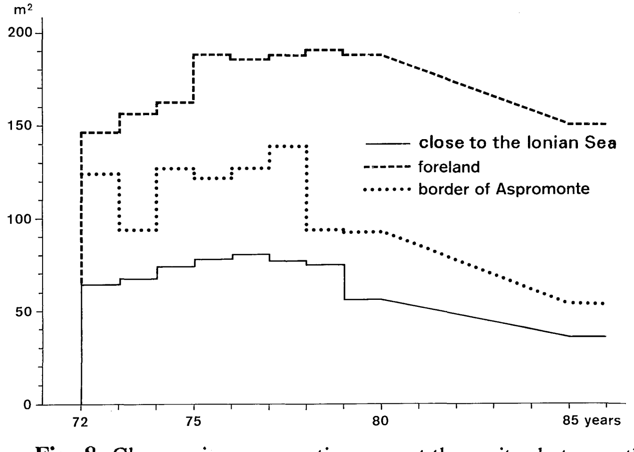

Fig. 8 Changes in cross-section area at three sites between the Aspromonte and the sea.

and the local input of large amounts of material by mass movements. The results of the investigations in the Buonamico basin have been drawn together in a conceptual geomorphological model (Fig. 9).

Seismic events and/or precipitation events cause vulnerable material on the steep slopes along the middle part of the valley to move by sliding. Triggered by extreme precipitation, landslides can occur approximately every 20-25 years, whereas earthquake events with a Richter scale magnitude above 8 have a recurrence interval of 100 years. In the Vallone Avrea, the remnants of such a huge event can be seen in a debris flow with a length of more than 2 km, a thickness of 50 m and a volume of 60×10^6 m^3. During this Holocene event, the river was incapable of evacuating all the material.

River bed dynamics operate at different time-scales. Indeed the river needs decades to overcome the local input of coarse material and to transmit this into the Ionian Sea. The difference between the reaction of the river system and the slope system is shown in Fig. 10. The volumes of sediment transport by river and landslides for various magnitudes differ considerably. Whereas the rivers dominate the low magnitude event field, mass movements dominate the high magnitude field.

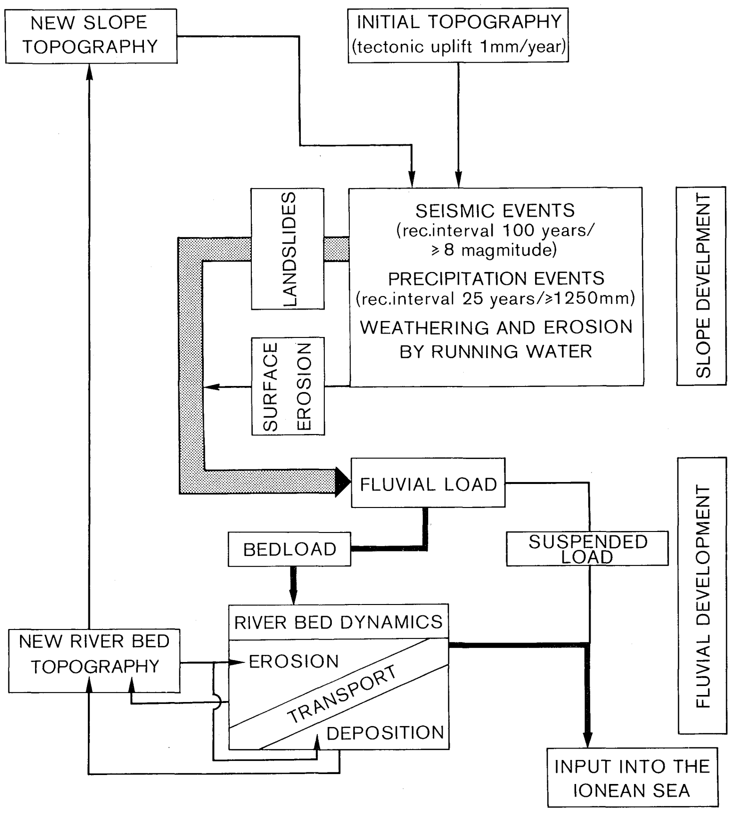

Fig. 9 Conceptual geomorphological model of the interrelationships between slope and fluvial development.

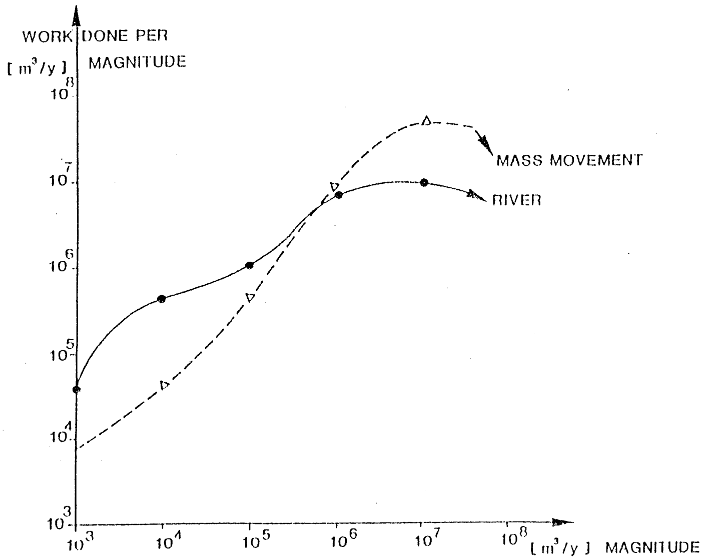

Fig. 10 Volumes of sediment transported by rivers and landslides in different magnitude classes.

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