Geogr. Fis. Dinam. Quat.
29 (2006), 125-137, 11 figg., 4 tabb.

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SENSITIVITY OF LANDSCAPE EVOLUTION AND GEOMORPHIC PROCESSES TO DIRECT AND INDIRECT HUMAN INFLUENCE

ABSTRACT: CENDRERO A., REMONDO J., BONACHEA J., RIVAS V. & SOTO J., *Sensitivity of landscape evolution and geomorphic processes to direct and indirect human influence*. (IT ISSN 1724-4757, 2006).

An assessment of some consequences of human activities on geomorphic processes during the last century is presented. The effects of urban-infrastructure development and mining on direct and indirect denudation and geologic materials transport in several study areas are analysed. The temporal occurrence of landslides is analysed in another study area. Results obtained are compared with data on denudation and sediment transport from the literature, as well as with data on geomorphic disaster trends for the same period.

Data obtained indicate that people are nowadays the main geomorphic agent. «Technological denudation» appears to be one or more orders of magnitude greater than natural denudation or sediment transport rates. The «human geomorphic footprint» or rate of anthropogenic landform construction could reach a total area of continental proportions by the end of the century. The frequency of geomorphic hazard events, at local, national and global levels, has increased about one order of magnitude in half a century and shows exponential growth trends, which appear to be correlated with GDP (gross domestic product).

It is proposed that growing population, wealth and technology (for which GDP can be used as an indicator) is the driving force behind a widespread «global geomorphic change» that affects landscape sensitivity. The effect of geomorphic change is added to that of climate change and implies an acceleration of landscape evolution rates as well as an intensification of geomorphic hazards. It is suggested that measures to mitigate geomorphic change should be taken in order to curb the observed trend towards increasing geomorphic disaster occurrence.

KEY WORDS: Landscape sensitivity, Human activity, Geomorphic footprint, Natural disasters, Global geomorphic change.

RIASSUNTO: CENDRERO A., REMONDO J., BONACHEA J., RIVAS V. & SOTO J., *Sensibilità della evoluzione del paesaggio e dei processi geomorfologici all'influenza umana diretta e indiretta*. (IT ISSN 1724-4757, 2006).

Si presenta una valutazione delle conseguenze dell'attività antropica sui processi geomorfologici nel corso dell'ultimo secolo. Gli effetti dello sviluppo urbano, delle infrastrutture e delle attività di cava e miniera sulla erosione e sul trasporto di materiali geologici è stato analizzato in diverse aree di studio, mentre la ricorrenza temporale di frane è stata analizzata in un'altra area di studio. I risultati ottenuti sono stati confrontati con dati sul denudamento e sul trasporto di sedimenti da bibliografia, così come con dati riguardanti le tendenze di disastri naturali per lo stesso periodo.

I dati ottenuti mostrano come l'uomo sia attualmente il maggior agente geomorfologico. Il «denudamento tecnologico» appare essere di uno o più ordini di grandezza maggiore del grado di denudamento e di trasporto naturali. La «impronta geomorfologica umana» o il grado di costruzione di forme antropogeniche potrebbe raggiungere un'area totale di proporzioni continentali alla fine del secolo. La frequenza di eventi di pericolosità geomorfologica, a livello locale, nazionale e globale, è aumentata di circa un ordine di grandezza in mezzo secolo e mostra un trend di aumento esponenziale, che pare essere correlabile al Prodotto Interno Lordo (PIL).

Si propone che l'aumento di popolazione, di benessere e di livello tecnologico (dei quali il PIL può essere utilizzato quale indicatore) sia il fattore forzante del generale «cambiamento geomorfologico globale» che influenza la sensibilità del paesaggio. L'effetto del cambiamento geomorfologico si aggiunge ai cambiamenti climatici, il che implica un'accelerazione del grado di evoluzione del paesaggio, così come un'intensificazione delle pericolosità geomorfologiche. Si suggerisce di adottare misure di mitigazione dei cambiamenti geomorfologici al fine di ridimensionare l'attuale tendenza all'aumento dei disastri naturali.

TERMINI CHIAVE: Sensibilità del paesaggio, Attività antropica, Impronta geomorfologica, Disastri naturali, Cambiamenti gemorfologici globali.

Mix common sense with foolishness; it is pleasant to let your mind wander occasionally. Horace (Odes).

INTRODUCTION

The concept of landscape sensitivity developed by Brunsden & Thornes (1979) refers mainly to the response of a geomorphic system to changes in the controls of, or forces applied to that system. This depends on the balance between disturbing and resisting forces. That concept has

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also been applied with a broader meaning, be it in the geomorphic sense or referring to landscape characteristics not directly or mainly related to geomorphic processes (Holling, 1973; Meade, 1982; Odum, 1983; Thomas & Allison, 1993; Rubio, 1995; Tallis, 1998; Thomas, 2001; Usher, 2001; Burt, 2001; Gordon & *alii*, 2001; Miles & *alii*, 2001; Brierly & Stankoviansky, 2003; Thomas, 2004; Heimsath & Ehlers, 2005). As pointed out by Brunsden (2001), changes in time and space resulting from the relationships above may involve morphological evolution and material transport. One important factor affecting landscape disturbing and resisting forces is human activity; it is therefore interesting to assess to what extent landscape evolution or processes related to it are sensitive to direct or indirect human influence. A possible approach to do this is the analysis of indicators that can be expressed quantitatively and are related to landscape evolution and dynamics.

One important indicator of the intensity of geomorphic processes affecting landscape evolution is the rate of geologic materials transfer from one part of the Earth's surface to another. The geomorphic evolution of landscape is strongly determined by landform changes related to erosion-sedimentation. In a steady-state situation, landscape evolution should proceed at more or less constant rates. However, if significant changes occurred in either disturbing or resisting forces, evolution rates would also change. Normally the rate of geologic materials transfer does not have important direct consequences for humans, although some indirect effects, such as sediment supply to river channels, dams or estuaries, are indeed significant from the human viewpoint. Another indicator of the intensity of geomorphic processes and their sensitivity to human influence is the frequency and/or intensity of hazardous geomorphic processes, such as floods or mass movements. This is certainly of much greater concern for people.

Landscape sensitivity to human influence is examined here from those two points of view. On the one hand, an assessment of the influence of human activities implying direct excavation and accumulation of solid materials (urban and infrastructure development, mining, quarrying) on denudation, materials transfer and sedimentation processes will be carried out. On the other hand, the sensitivity of landslide processes to human-induced changes on the Earth's surface will also be analysed. Both effects are specific manifestations of the role of people as a geomorphic agent and have some broader implications. This paper builds on the results of two previous contributions by the authors (Remondo & *alii*, 2005; Rivas & *alii*, 2006) using additional data and analysing some implications of the former analyses for our understanding of the way geomorphic processes have operated in the recent past and might operate in the near future, as well as the consequences of this for hazard and risk assessment.

GEOMORPHIC EVOLUTION OF LANDSCAPE

Geomorphic evolution of landscape is due to different natural agents: mass wasting, wind-, ice- and water-driven processes, mainly rivers. One net result of those processes is the transfer of earth materials from denudation to deposition areas, with the consequent softening of relief. But landscape evolution is also determined by human activity. The role of humans on changes affecting the planet's surface was already examined quite a long time ago (Marsh, 1877; Thomas, 1956; Brown, 1956). Since then, considerable efforts have been devoted to analyse the consequences of human activities for climate or the biosphere and also of soil erosion related to farming or forestry activities. Some analyses of the effects of other types of activities on Earth's surface processes have been carried out (Archer & *alii*, 1987; Goudie, 1984, 1993, 1995; Douglas, 1990; Luttig, 1992; Walling, 1996; Brierly & Campbell, 1997; Phillips, 1999; Naredo & Valero, 1999; Slaymaker, 2000). But fewer studies have been undertaken on the significance of urbanisation, infrastructure development, quarrying and mining as geomorphic processes (Hooke, 1994, 1999).

Geomorphic materials transfer is increasingly influenced by human activity, through both direct, deliberate excavation/accumulation (construction, mining) and indirect, induced erosion (construction, mining, forestry and farming). Those activities also imply the construction of new «geomorphic units» (Cendrero & *alii*, 1987), each one of them with characteristic landforms, materials and processes (mining and quarrying excavations or accumulations, built-up areas etc). Excavation and accumulation activities also enhance natural erosion processes, thus indirectly contributing to materials transfer, sediment supply and landform evolution (Wolman, 1967; Wolman & Schick, 1967; Dunne & Leopold, 1978; Sowa & *alii*, 1990; McClintock & Harbor, 1995; Walling, 1996; Trimble, 1997; Harbor, 1999; Rawat & *alii*, 2000; Lu, 2005). About half a century ago Brown (1956) suggested that «technological denudation» could reach 3.3 mm a^{-1} in a world with 30 billion people. By technological denudation it was understood the mobilisation of earth materials by different types of excavation. If this was correct, it certainly would represent a major contribution to geomorphic landscape evolution.

An assessment of the importance of human contributions to earth materials transfer and landform evolution compared to natural processes has been carried out (Rivas & *alii*, 2006). That assessment provides some insight into the sensitivity of landscape evolution processes to human influence. The assessment was based on the analysis of geomorphic effects of urban development, mining activities and infrastructure construction in several study areas, one in an industrialised country (Besaya valley, Spain) and three in an emerging one (La Plata, Mar del Plata and Rio Cuarto, Argentina). The nature of the study areas and the methodology used in the analysis are explained in the aforementioned contribution and only a brief description is presented here. The effect of urban and infrastructure development as well as mining/quarrying activities on landscape evolution were assessed on the basis of their contribution to materials transfer and creation of new, anthropogenic landforms.

Materials mobilisation rate by those activities can be expressed as:

$$MR = DERui + DERmq + IDRuimq$$

Where: MR = mobilisation or transfer rate; DER = direct excavation rate; IDR = indirect denudation rate of disturbed areas; u = urban; i = infrastructure activities; m = mining; q = quarrying. All terms of the equation can be expressed as either $m^3\ m^{-2}\ a^{-1}$ or mm a^{-1}.

The contribution to landform generation can also be expressed in terms of the «geomorphic footprint» (area of anthropogenic landforms produced and volume of geologic materials transferred, per person and year; Rivas & *alii*, 2006), a concept in a way related to the ecological footprint (Wackernagel & Rees, 1996), but with quite a different meaning.

The extent of urban areas was determined by means of maps and air photographs of different dates. Data on population were also obtained. *Per capita* use of urban space in the study areas was thus calculated for the period covered and is shown in fig. 1. Rate of urban land occupation (or urban landform construction) was calculated for the periods 1985-2000 and 1995-2000, and the results are presented in fig. 2. The period considered is short and the area occupied by constructions very small compared to total available area. Obviously, if growth continues, the rate would eventually decrease as built-up area approaches total available area (in a very distant future).

Despite certain irregularities in some of the study areas, probably due in part to the different nature of data (annual values for population; irregular periods for urban area, conditioned by the availability of maps or air photographs), it is clear that urban space occupied per person has grown with time, reaching rates between 2.5 and 5 m^2 $pers^{-1}\ a^{-1}$ at the end of last century (fig. 2). This is probably the consequence of increasing wealth, with wealthier study areas (Besaya, Mar del Plata) showing higher growth rates. Average excavation for the different types of urban areas was also determined as well as volume directly affected by urban activities determined. As excavation depth has grown with time (higher buildings, deeper foundations, more utilities etc), there is little doubt that volume rate has grown more markedly than area rate, even though exact figures are not available. In summary, «urban geomorphic footprint» expressed as rate of area of new landforms originated and geologic materials directly excavated grows with time, reflecting the growth in human capability to intervene on the Earth's surface (more people, wealth and technology, that is greater GDP).

Mining activities also represent an important contribution to the human geomorphic footprint. Data on the extraction of earth materials through mining and quarrying were obtained in the four study areas, directly through air photo and field surveys or from public and mining companies' records. Finally, data were also obtained on areas and volumes affected by infrastructure construction. Full details on the procedures used and data obtained are given by Rivas & *alii* (2006). A summary of the results is shown

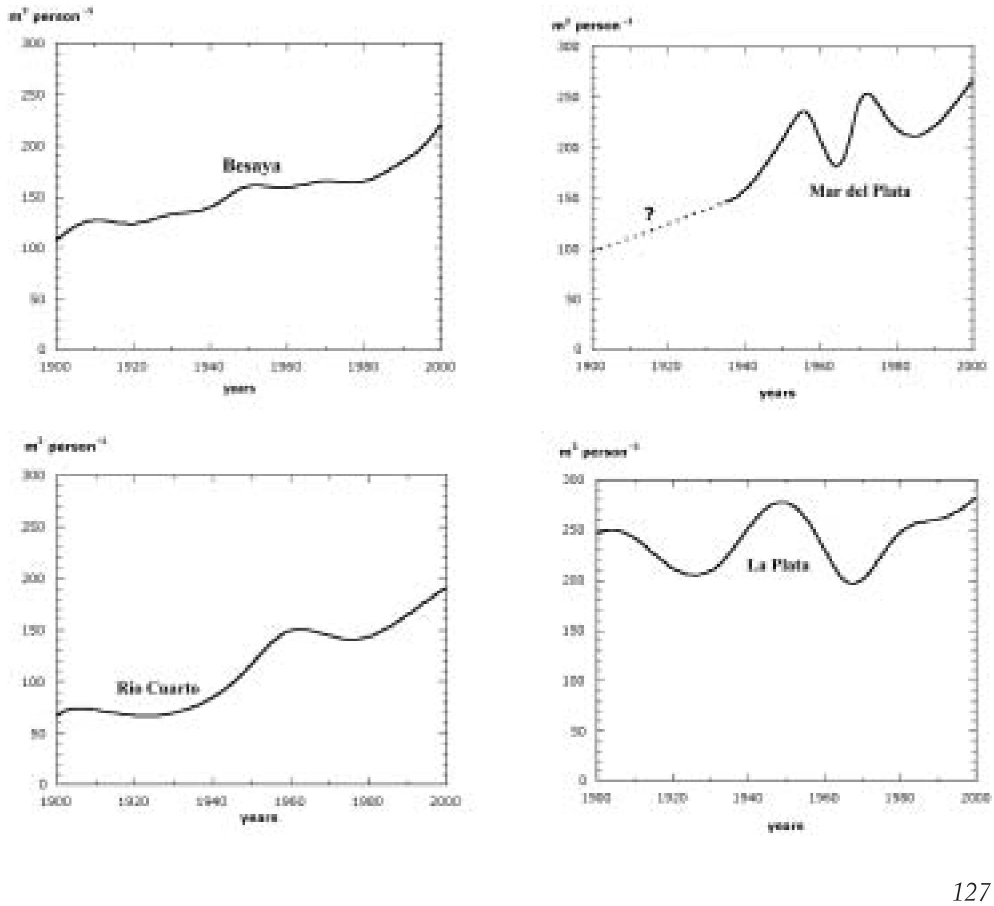


FIG. 1 - Evolution of *per capita* use of urban space (urban area divided by number of inhabitants) in four study areas: Besaya valley, Spain; La Plata, Mar del Plata and Rio Cuarto, Argentina (Rivas & *alii*, 2005).

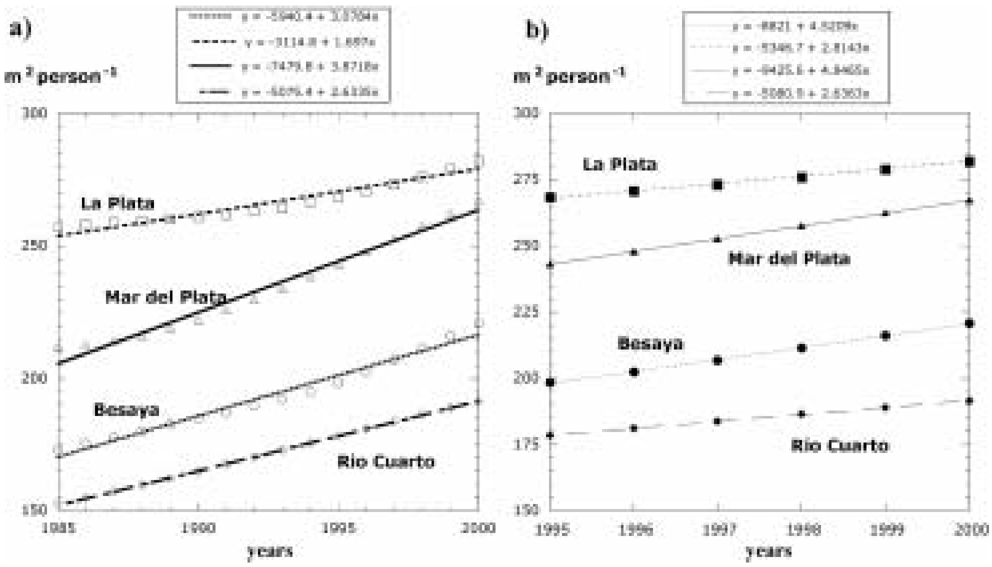


FIG. 2 - Rate of urban land use for the periods 1985-2000 (a) 1995-2000 (b) (Rivas & *alii*, 2005).

in fig. 3, which also includes, for comparison, data on the Madrid region (Naredo, 2002).

Areas affected by excavations and accumulations, in which materials are profoundly disturbed and vegetation cover eliminated, are much more erosion-prone than other areas. Induced erosion in that type of disturbed surfaces was assessed in the study areas, through direct determinations and indirect estimates based on the USLE (Wischmeier & Smith, 1978) as well as from the literature (Marelli & *alii*, 1985; Nogués, 1987; Arce, 1988; Edeso & *alii*, 1991; Díaz de Terán & *alii*, 1992; Cantú & *alii*, 1996; Cendrero, 2003; Rivas & *alii*, 2006). Finally, in order to compare the magnitude of direct and indirect human contributions to geologic materials transfer with the one due to natural processes, erosion rates in undisturbed, nearly-natural areas were determined, estimated and obtained from the literature (Nani & *alii*, 1980; Salas, 1993; Cendrero & *alii*, 1994; González-Díez & *alii*, 1996, 1999; Becker & *alii*, 2002; Bujan & *alii*, 2003).

Results are summarised in table 1. For comparison purposes, total volumes affected by direct excavation and induced erosion of disturbed areas have been considered as if they were uniformly distributed over the whole study area analysed and expressed as rates (mm a^{-1}). It is clear that in all study areas the process of materials mobilisation is largely dominated by direct excavation. Induced erosion of disturbed surfaces, even though these represent a minor proportion of the study areas analysed, appears to be generating as much sediment – or even more – as natural erosion over the whole of all such areas. In other words, the process of geomorphic evolution of landscape (from the point of view considered here) in these study areas seems to be extremely sensitive to human influence, with natural processes presently playing a very secondary role.

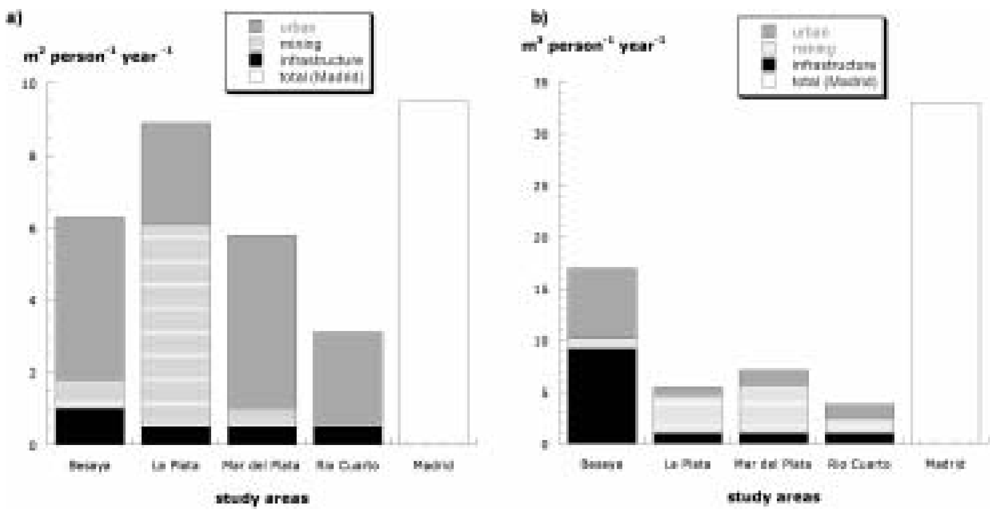


FIG. 3 - *Per capita* rates of area used (a) and volume excavated (b) for urban, infrastructure and mining/quarrying activities in four study areas for the most recent period available in each case (from data in Rivas & *alii*, 2005).

TABLE 1 - Comparison between direct, indirect and natural mobilisation processes (mm a^{-1}) (Rivas & *alii*, 2005)

Zones	Direct excavation	Induced erosion(1)	Present erosion(2)
Besaya	3	0.05-0.25	0.01
La Plata	3.3	0.02	0.01
Mar del Plata	2.7	0.01	0.01
Rio Cuarto	9.5	0.09	0.05
Other humid Pampa			0.01

(1) Sediment contribution from disturbed areas evenly distributed over the whole study area.
(2) Under «nearly natural» conditions.

The study areas analysed are more densely populated than the world average. Thus, in order to get an idea of the relative importance of the processes considered at a global level some extrapolations were made on the basis of *per capita* contribution. *Per capita* effects due to construction activities are produced essentially within the areas themselves. On the other hand, a large proportion of mining materials directly or indirectly used by people are extracted far away. These are basically ores, coal and construction materials not included in the analysis of the study areas. Data from mining statistics for Spain, Argentina and the World (Naredo & Valero, 1999; IGME, 2002; SEGEMAR, 2002) were used to calculate *per capita* contribution to mining mobilisation. Adding this contribution to the values obtained in the study areas, the overall geomorphic footprint attributable to the activities considered was thus calculated and is presented in table 2. Hooke (1994, 1999) obtained similar – although a bit smaller – values for direct excavation of earth materials. Data provided by Adriaanse (1997), Eurostat (2002), Carpintero (2003) and Arto (2003) on use of non-biotic materials in industrialised countries range between 33 and 76 t $pers^{-1}$ a^{-1}. Material types considered by those authors are not directly comparable to the ones used in this analysis, but their values are clearly within the same order of magnitude as ours.

It is interesting to compare the rates presented above with those obtained by different authors for natural denudation processes (table 3). Comparisons must be made with caution. The values we have obtained have a margin of uncertainty and should be considered as valid at the order-of-magnitude level. The uncertainty also exists in the case of natural rates, as shown by the differences in the values provided by different authors. The nature of the processes compared is not the same. Also, natural denudation affects the Earth's surface in general, whereas the influence of human activities analysed is concentrated in a much smaller area.

TABLE 2 - Total geomorphic footprint (approximate values*) due to excavation and mining activities. (Modified from Rivas & *alii*, 2005)

Region	Area rate (m^2 $pers^{-1}$ a^{-1})	Volume rate (m^3 $pers^{-1}$ a^{-1})	Total area (km^2 a^{-1})	Total volume (x 10^6 m^3 a^{-1})	Mobil. Rate (mm a^{-1})
Spain	7.9	30.4	316	1216	2.4
Argentina	5.93	6.4	213	230	0.08
World (?)	6.91	18.4	41,460	110,400	0.83

* World values are a rough average obtained assuming that global rates are probably somewhere between those of an industrial and one emerging economy and should not be considered as a rigorous estimate.

TABLE 3 - Lowering rates (mm a^{-1}) according to different authors (Leopold & *alii*, 1964; Douglas, 1990; Summerfield & Hulton, 1994; Goudie, 1995; Hallet & *alii*, 1996; Remondo, 2001; Gellis & *alii*, 2004; Renwick & *alii*, 2005; Sigha-Nkamdjou & *alii*, 2005, Latrubesse & *alii*, 2005)

Author (year)	Place	Rate	Observations
Clark & Jagger (1964)	Alps	0.004-1	
Corbel (1964)		0.03-0.15	Temperate humid or subhumid areas
Leopold et al. (1964)	World	0.027	
Eardly &Viavant (1967)	Utah	0.14-0.067	
Ruxton & McDougall (1967)	Papua	0.06-0.8	
Strakhov (1967)		0.03-0.08	Large river basins
Young (1974)		0.1-0.5	Mountain areas
Owens & Watson (1979)		0.01-0.05	Lowlands
Selby (1982)	Mississippi valley	0.04	
Judson (1983)	World	0.06	From original brute data
Judson (1983)	World	0.025	Natural contribution
Saunders & Young (1983)	World	0.01-1	
Crocier (1984)	New Zeland	0.03-0.5	Forest areas
Cendrero & Díaz de Terán (1985)	Canary Islands	0.27	
Benito et al. (1991)	Galicia	0.01	
Summerfield & Hulton (1994)	World	0.004-0.68	Major drainage basins
Nava (1995)	Bárdenas Reales	4-10	
Hallet et al. (1996)	Glaciated regions	0.01-100	
Briggs et al. (1997)	World	0.065	From original brute data
Gellis et al. (2004)	New Mexico	0.05-1.5	
Latrubesse et al. (2005)	34 large tropical rivers	0.002-2.0	From sediment yield data
Renwick et al. (2005)	Ohio	0.1-1	
Sigha-Nkamdjou et al. (2005)	Cameroon	0.005-0.1	

If the figures presented above (for one emerging and one industrialised economy) are correct and more or less representative of possible value ranges, we would have that "technological denudation" is about one order of magnitude greater, or more, than natural denudation. That is, the geomorphic process of materials transfer and relief evolution appears to be controlled essentially by the human activities analysed, that seem to contribute with at least 90% of the total denudation.

The human geomorphic footprint – expressed as rate of generation of new landforms – is at present probably about 40,000 km^2 a^{-1} (Rivas & *alii*, 2006). Taking into account the trend towards increasing geomorphic footprint, the total area covered by new «anthropogenic landforms» could reach continental proportions at the end of the century, probably in the order of 5-10 x 10^6 km^2. The total volume mobilised through human activities, presently about 10^{11} m^3 a^{-1}, would increase even more markedly. It thus appears that landscape evolution processes assessed here are also very sensitive to human influence when considered at global level.

GEOMORPHIC PROCESSES AND HAZARDS

What has been presented above indicates that human action has become an increasingly important agent during the last century, particularly in the last few decades. A logical question that arises then is to what extent specific geomorphic processes, particularly those representing hazards, are sensitive to human influence. This issue was raised quite a long time ago, particularly with respect to floods (White, 1945; Kates, 1962; Burton & Kates, 1964; Goddard, 1976; Hewitt, 1983; Smith, 1996) and has continued receiving attention (Capelli & *alii*, 1997; Pielke, 2000; Yin & Li, 2001; Johnson & Warburton, 2002).

A look at a few data on some socio-economic and natural hazards indicators provides a few clues with respect to that. Figure 4 shows the evolution of world population, energy consumption and gross domestic product (GDP) during the second half of last century. Between 1950 and 2000 population has increased approximately by a factor of 2.4, energy consumption by 3.8 and GDP by 6.8. This reveals a growing degree of industrialisation and a clear improvement in the management of economic systems (productivity per unit energy consumed and even more per person has increased considerably). Figure 5 (EM-DAT, 2005; Munich Re, 2005) shows data on natural disaster events and damage. Natural disasters and damage have increased by a factor of about 12 and 25-30, respectively. Both natural hazard events and damage – especially the latter – grow more than socio-economic indicators that might be somehow related to them. If our management in this realm had remained at the same level of efficiency we should expect damage to grow approximately the same as GDP (more elements to be damaged, more damage). Reported losses could be influenced by a variety of factors but if we accept the data presented, we should come to the conclusion that losses per person or per unit GDP are greater now than in the past. In other words, the overall result of our management of natural hazards has become worse. Could this growing losses and, especially, growing number of natural hazards events be due, at least in part, to geomorphic changes?

An analysis of the evolution of landslide frequency or rates in a study area of northern Spain, the lower Deva valley, during the second half of last century provides additional data. An inventory of landslides occurred in the area between 1954 and 1997 was carried out. Details on the procedure have been presented by Remondo (2001), and Remondo & *alii* (2003a, 2003b, 2005). Figure 6 shows the variation of landslide frequency in the study area. It can be seen that frequency has increased by a factor of about 10 in less than 50 years. The trend is similar when landslide mobilisation (volume of material affected by landslides) rate is considered.

Climate data for the area (Diputación Foral de Guipúzcoa, 1999; Remondo, 2001) do not explain the trend observed. It rather appears that the increasing frequency is somewhat related to human influence, as suggested by data in fig. 7. Although the correlation between both variables is by no means ideal, data shown suggest this might not be a simple coincidence. Gross domestic product (GDP) is an indicator of the human capability to intervene on the Earth's surface (growing GDP implies growing

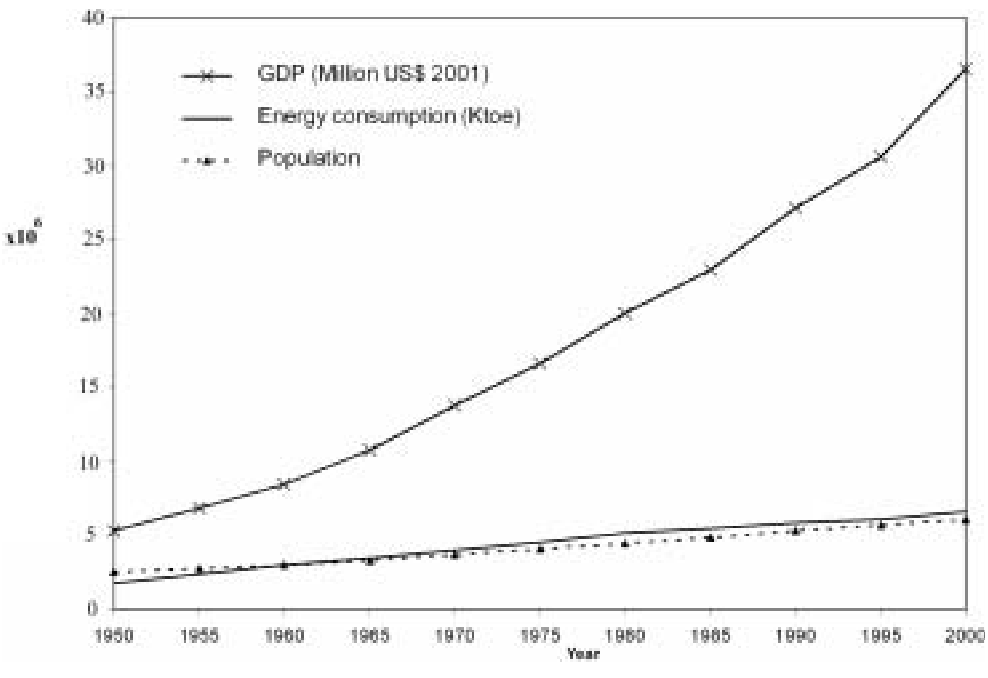
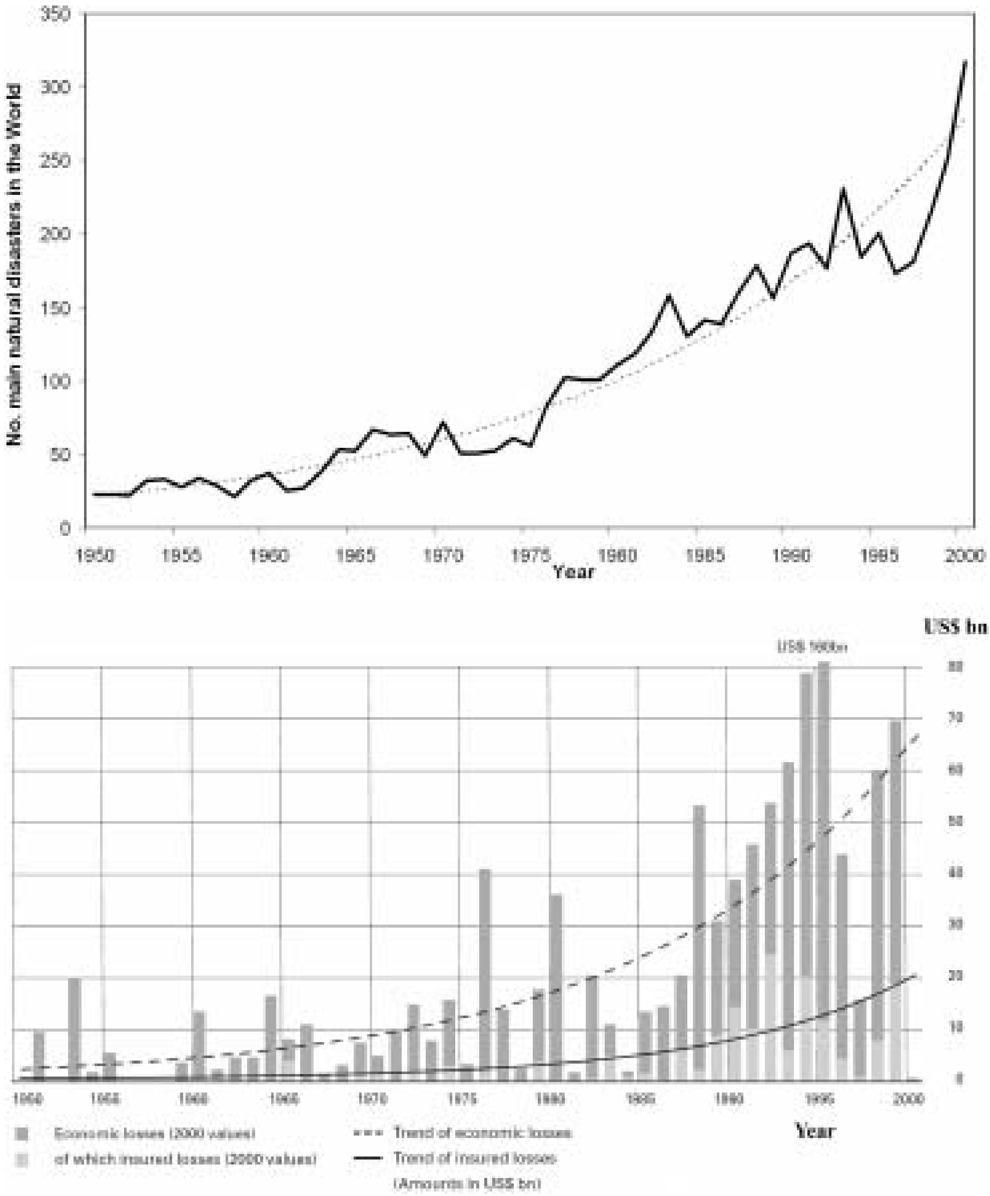


FIG. 4 - Evolution of world population, energy consumption and GDP for 1950-2000 (Groningen Growth and Development Centre and The Conference Board, Total Economy Database, August 2005, http://www.ggdc.net; United Nations Population Division, October 2005, http://www.un.org/esa/population/unpop.htm; International Energy Agency, October 2005, http://www.iea.org/).

FIG. 5 - Number of natural hazards events (EM-DAT, 2005) and damages (Munich RE, 2005) in the world during the second half of last century.



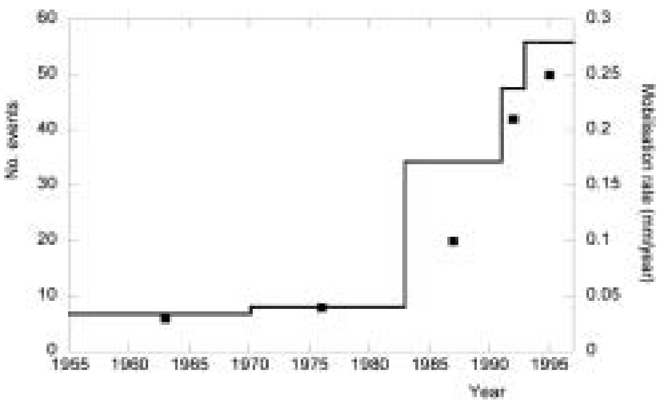


FIG. 6 - Landslide frequency and mobilisation rate in the Bajo Deva area, northern Spain, during the second half of last century (from data in Remondo & *alii*, 2005).

population, wealth and technology). This growing capability is normally translated into more urbanisation, infrastructure construction, quarrying for construction materials, more intensive agricultural and forestry techniques etc. This brings about changes in the surface layer that might trigger landslides. Remondo (2001) points out that at least 7 per cent of the landslides inventoried during the period were clearly triggered by human actions and that an additional 25 per cent present evidence of a possible human influence. But it also produces more subtle, widespread changes (regolith modifications due to more intensive agricultural technologies, repeated land-use changes, diversion of surface runoff and related variations in saturated and unsaturated layer conditions due to house, road and track construction or improvement) that may affect the resilience of the surface layer, increasing its sensitivity to natural trig-

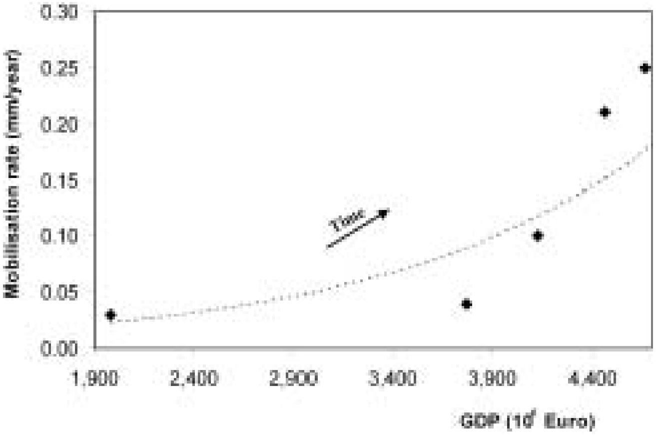


FIG. 7 - Correlation between landslide mobilisation rate and GDP in the Bajo Deva area (Remondo & *alii*, 2005).

gers. This is probably the explanation for the great difference between the large numbers of landslides produced in the area during the intense rains of August 1983 and the much smaller ones during similar rainfall episodes in the 50's and 60's.

Is the situation described above of a local character or could it represent a more general trend? If the relationship suggested above was true, it should be observable in other areas and at different scales. Figure 8 shows the variation in the number of landslides in Italy during last century (Guzzetti & Tonelli, 2004), as well as number of different types of natural disasters in the world (EM-DAT, 2005). The frequency trend for landslides in Italy is quite similar to the one observed in our study area (fig. 6).

Global data show a marked increase in the number of all the types of disasters considered from around 1950. This increase might be in part apparent, due to better information, or attributable to the fact that a growth in the number of exposed elements (people, buildings, infrastructure etc) should result in a greater number of disastrous events even if the behaviour of processes does not change. That might be the explanation for the relatively limited growth shown for geological disasters (mainly earthquakes and volcanoes, processes obviously not affected by human activities). It could be a coincidence but the growth in the number of these disasters is similar to GDP growth during the same period. All other disasters represented, related to climate or atmospheric processes, show a much greater increase that cannot be explained by better information or greater exposure. They are more likely to reflect climate change which includes an increase in the frequency of extreme events (IPCC, 1996; UNEP, 1997; IPCC, 2001; Moreno, 2005).

But clearly the sharpest increase is shown by disasters due to what we can consider as geomorphic hazards (floods and related, which include most mass movements). A comparison between the trend shown by those events and the ones obtained for the Deva study area and Italy reveals an interesting similarity. Is this a simple coincidence? Do perhaps the three graphs reflect the same sort of relationship between socio-economic drivers (represented by population, wealth and technology growth) and increasing sensitivity – or decreasing resilience – of geomorphic systems? If that is the case, we would have that the trends for «floods and related» in fig. 8 might be the result of «global climate change» and "global geomorphic change", both of them driven by the present model of economic development.

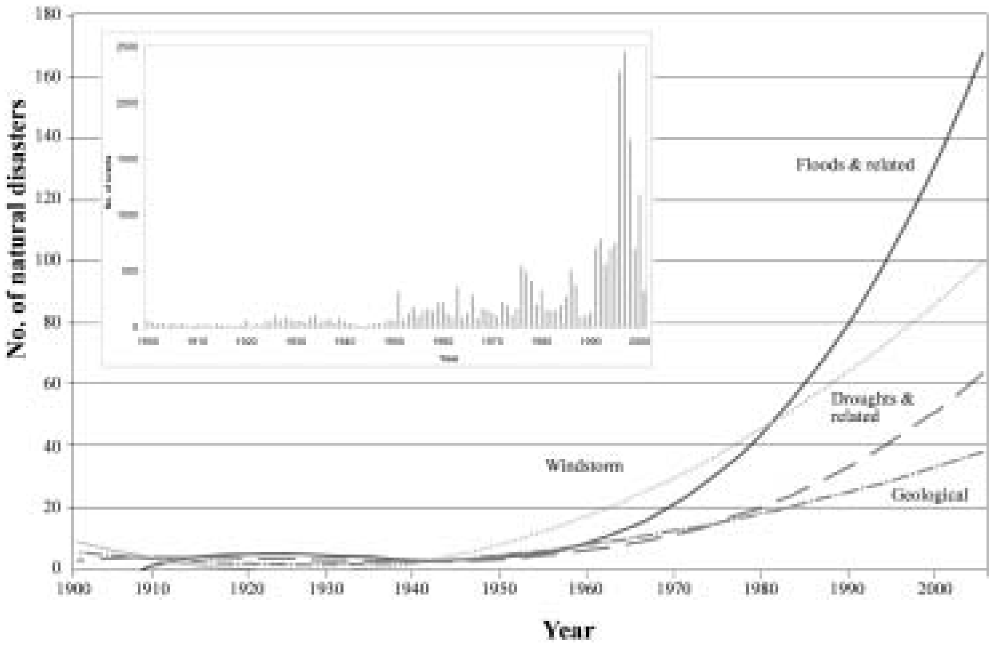


FIG. 8 - Number of landslide events in Italy (Guzzetti & Tonelli, 2004) and worldwide polynomial trends for the major types of natural disasters (EM-DAT, 2005).

A NEW GEOMORPHIC EVOLUTION MODEL?

The results presented above suggest that geomorphic processes have experienced a significant change during the last century, particularly during the last few decades, reflecting a growing human influence. On the one hand, it appears that denudation («technological denudation»; Brown, 1956), geologic materials transfer and generation of new landforms – all of them manifestations of landscape evolution – have increased markedly as a result of direct human activity. The figures obtained indicate that technological denudation (especially if we consider both direct excavation and induced denudation) is probably by far the main contributor to overall denudation. The growing *per capita*, human geomorphic footprint reflects the growth in wealth and technological capability. A larger population with more wealth and technological capability implies, obviously, a larger GDP. It is therefore not surprising that GDP (an expression of human capability to act upon and modify the Earth's surface) and some of the consequences of an increasing human intervention on geomorphic systems show a certain relationship.

Another way to assess the relative importance of human transfer of geologic materials is to compare it with sediment transport to the ocean by the world's rivers, the main geomorphic transport agent. Table 4 presents values on sediment transport to world oceans, obtained by different authors. It must be borne in mind that upland denudation is not necessarily equivalent to sediment deposition at the river mouth. Sediment produced in upland areas may remain stored in the watershed for years or even more than a century. Thus the amount of material eroded at a given time may be significantly greater than the amount of sediment carried by rivers draining the area (Trimble, 1981; Meade, 1982; James, 1989; Marcus & Kearny, 1991; Slaymaker, 1993), although eventually it will end up in the sea. Having this present and also the fact that rivers are not the only transportation agent it is nevertheless interesting to compare the values in table 4 with those in table 3; they are essentially of the same order of magnitude. That is, «anthropogeomorphic» materials transfer also seems to be one or more orders of magnitude greater than fluvial sediment transport (or total sediment transport; Hay, 1998).

TABLE 4 - River sediment yield (x10^6 t a^{-1}) to the oceans (from Judson, 1983; Hay, 1998; Syvitski & *alii*, 2005)

Authors	x 10^6 t a^{-1}
Lopatin (1950)*	17,500
Kuenen (1950)+	32,500
Fournier (1960)+	58,000
Barth (1962)	3,800
Schumm (1963)+	20,500
MacKenzie & Garrels (1967)+	8,300
Judson (1968)	24,000
Holeman (1968)+	18,300
Holland (1978)	20,000
Judson (1983)°	9,300
Milliman & Meade (1983)	13,505
Milliman & Syvitski (1992)	10,000-20,000
Syvitski & *alii* (2005)	15,500 - Pre human
Syvitski & *alii* (2005)	17,800 - Present

° only naturally produced sediment
* does not include bed load
\+ only solid load

Considering the indirect influence of other activities (agriculture, forestry, which account in part for the values in tables 3 and 4), that seem to account for about 50% of solid sediment load in rivers (Judson, 1983; Hay, 1998), the importance of the human role would be even greater. It appears that the geomorphic system mountain-river-sedimentation basin, which has been the main agent of solid materials transfer on the Earth's surface until recent times, has been substituted to a great extent by the «anthropogeomorphic system» quarry/mine – road/railway – urban/industrial agglomeration. If that is so, the question would not be whether geomorphic landscape evolution is sensitive to human influence, but whether natural processes are quantitatively significant for present geomorphic transfer.

Increasing human capability to intervene on the surface layer might also be resulting in a growing degradation and de-stabilisation of geomorphic systems. This could be reflected in increasing rates of certain geomorphic processes. Something quite similar has been pointed out by Glade (2003) in New Zealand, where land use changes following European colonisation were «the most important factor leading to increased landslide initiation» and consequent increases in sedimentation rates in lakes, wetlands and estuaries (by a factor between 1.6 and 18.2). A clear example of de-stabilisation of a different geomorphic process through human influence has been presented by Knox (2001), who shows the sensitivity of flood frequency and magnitude to changes due to human activity.

As discussed above, it seems that human influence is increasing landscape sensitivity to natural landslide triggers and causing an increase of landslide rates in the lower Deva area of northern Spain. If that is so and considering that mass wasting is a very important denudation mechanism in the region, an increase in the final result of geomorphic processes, sediment transport to deposition areas, should be expected. Figure 9 shows data on sedimentation rates determined in estuaries of northern Spain, different from that of the Deva River, where the analysis of landslide rates was carried out. The periods covered are not the same and the type of data obtained are different, but it is clear that the increase of sedimentation rate is quite similar to the one observed for landslide rate. In both cases, the trend towards increasing rates with time is quite apparent, suggesting that the relationship between growing human influence (GDP) and acceleration of geomorphic processes is also valid in those valleys and probably not a coincidence or a local effect.

Could it be that we have a chain of increasing effects of the type shown in fig. 10? Socio-economic drivers would be reflected in a growing «human geomorphic footprint», with an intensification of the generation of anthropogenic landforms, greater human role in the transfer of earth ma-

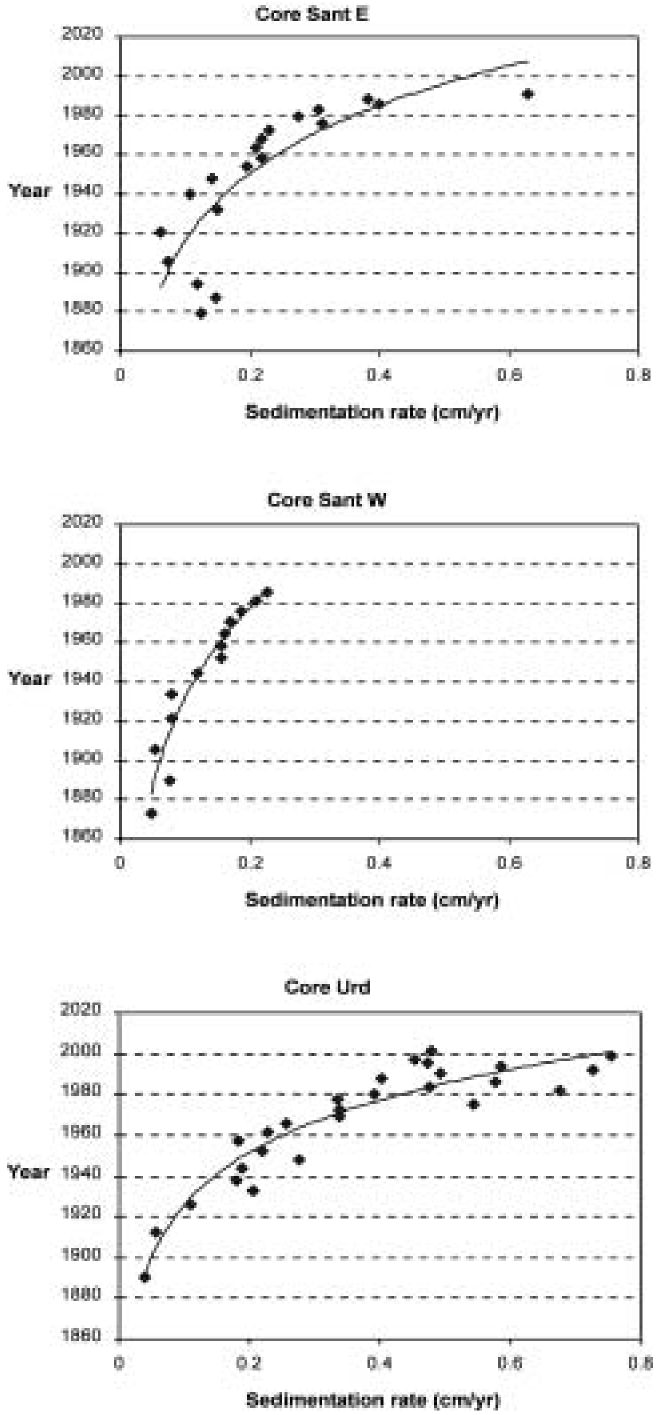


FIG. 9 - Sedimentation rates in three cores from estuaries in the north coast of Spain (Remondo & *alii*, 2005).

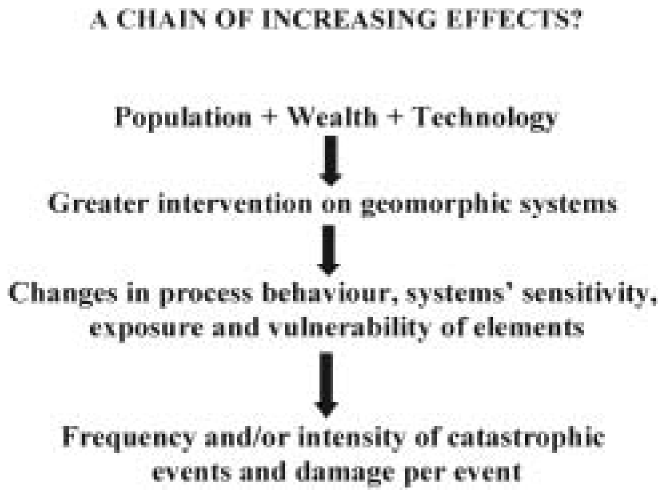


FIG. 10 - Possible chain of increasing effects linking socio-economic drivers and response of geomorphic systems. Each step probably has a multiplying effect.

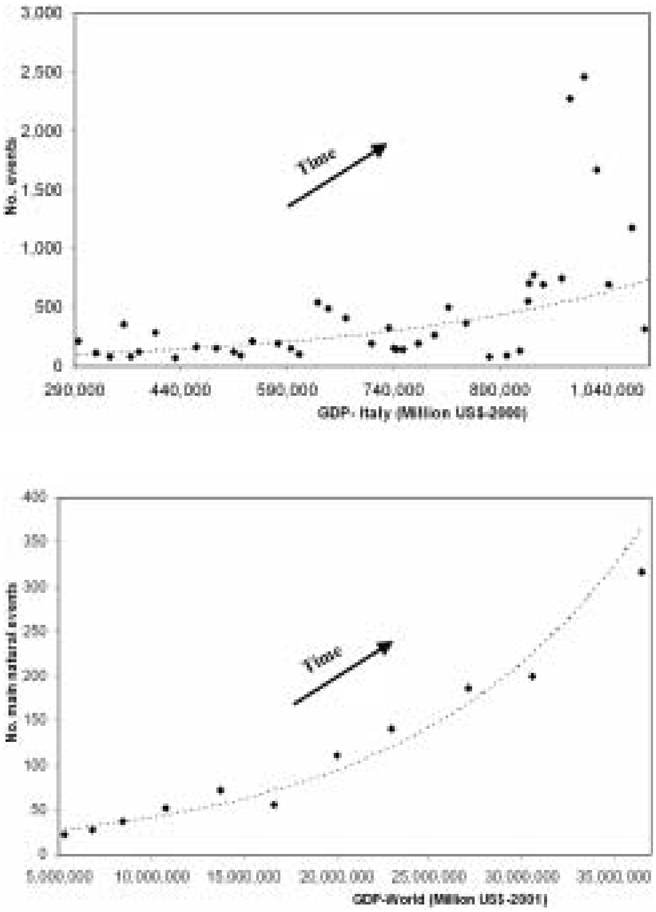


FIG. 11 - Relationship between GDP and number of landslides in Italy and floods and related disasters in the world. (Data from Guzzetti & Tonelli, 204; EM-DAT, 2005 and Groningen Growth and Development Centre and The Conference Board, Total Economy Database, August 2005, http://www.ggdc.net).

terials and relief evolution, as well as greater sensitivity of geomorphic processes, with the consequent acceleration of rates. The relationship between GDP and number of events (landslides in the Deva valley, Spain and in Italy; floods and related disasters at global level) shown in fig. 11 suggests that this might indeed be the case.

In a review paper of the contents of a special issue of Catena, Brierly & Stankoviansky (2003) comment that «whether land use change or climate change is the main trigger of accelerated erosion-accumulation processes in long term landscape evolution remains uncertain... however... it is clear that... land use changes decrease the boundary resistance of landscape to change». These modifications increase landscape sensitivity and increase the effects of relatively small climate changes. The results presented in this work suggest that changes directly produced or indirectly induced by human activity have indeed been the main controllers of landscape evolution in the last few decades. In other words, during that period landscape has been much more sensitive to «geomorphic change» than to «climate change».

Perhaps we should start to think that the present model of geomorphic evolution represents a novelty in Earth's history. Up to well within the 20^{th} century, geomorphic landscape evolution and geomorphic processes were determined by water as the main agent. From about the middle of last century humans seem to be the dominating geomorphic agent, and rates of geomorphic processes have probably increased by one or more orders of magnitude. It appears that a transition has taken place from a «pre-industrial» to a «post-industrial» geomorphic model (Rivas & *alii*, 2006), significantly different form the former, in both qualitative and quantitative terms.

If that is correct, we should be extremely cautious when making geomorphic hazard and risk assessments. These assessments are normally based on the analysis of past behaviour of processes, determination of trends and construction of models to make predictions about future behaviour (the uniformitarian assumption). Data presented above suggest this assumption might not be justified and that intensity of geomorphic processes, frequency and magnitude of extreme events are likely to increase considerably during the present century. We should therefore try to gain a better understanding of the relationships between socio-economic and geomorphic processes in order to adjust to the hypothetical «new geomorphic model» and improve the quality of our predictions.

It seems that, as in the case of climate warming, we may have a coupling between socioeconomic development and «global geomorphic change» manifested through increasing human geomorphic footprint and rates of geomorphic processes and hazards. If that proves to be true, it would be necessary to design and implement policies aimed at producing a decoupling between both processes. The importance of working towards such decoupling is quite apparent looking at the figures about natural hazards and risks presented. Should we perhaps think about some sort of «Kyoto Protocol» to ensure that proper land-use management policies and practices, respectful with the nature and dynamics of geomorphic systems, are implemented?

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(Ms. received 11 November 2005; accepted 31 July 2006)