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# Erosion and sediment yield in mountain regions of the world

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**Abstract** A comparative assessment of erosion intensity in mountain regions of the world has been made based on suspended sediment yield data from 1872 mountain rivers. Quantitative analysis indicates that erosion in mountain regions depends on climate and runoff, landscape character and the degree of economic development, relief, recent tectonic activity, and underlying geology. The most intensive erosion and denudation are found in the glacial and subnival zones, whilst the mountain taiga zone is the least eroded area. A combination of zonal and azonal factors conducive to erosion have given rise to extremely intensive erosion in the mountain areas of east and southeast Asia and New Zealand. In the forest zones, channel erosion dominates slope erosion. Where forest cover is absent due to either natural conditions or anthropogenic activity, slope erosion and denudation become the principal source of sediment in the river network. Depending on the predominance of either channel or slope erosion, two types of mountain erosion systems can be distinguished: in the first sediment yield depends on the basin area directly, in the second the relationship is indirect.

## INTRODUCTION

Sediment yield is not an accurate measure of all the products of erosion and mechanical denudation, since a considerable part of the latter is accumulated in the form of slope, proluvial, and alluvial deposits and is not transported to the outlet of the drainage basin. Delivery ratio coefficients, representing the ratio of the material transported out of the basin to all the products of mechanical denudation, may only be used to provide a tentative assessment of the total denudation, since even in mountain basins this ratio does not exceed 0.5. Nevertheless, sediment yield directly depends on the intensity of erosion and the overall mechanical denudation in the river basin and can be used for comparative assessments of the intensity of these processes under different conditions. The aim of this article is to provide a quantitative assessment of the intensity of erosion in mountain regions caused by major natural and anthropogenic factors.

## DATA SOURCES

For characterizing erosion, we collected and synthesized data on suspended sediment yield for 3700 river basins from around the world, including 1872 in mountain regions. Bed load data were obtained for 269 basins, including 158 in mountain areas. For all these basins we collected and presented data on the area, height or type of relief, runoff, underlying geology, landscape patterns, and the degree of anthropogenic modification of the landscape (Dedkov & Moszherin, 1984). Most were from mountain regions of Europe (Caucasus, Carpathians, Alps, Appenines, Scandinavian Mountains, Urals, and Balkan Mountains), North America (the mountainous west of the USA and Canada and the Appalachians), Asia (Pamirs, Tien Shan, the mountains of Siberia, Indo-China, and the Hindu Kush), New Zealand, and southern Africa. There were few data for the mountains of Australia and South America.

The sediment yield per unit area or specific sediment yield (t $km^{-2}$ $year^{-1}$) was taken as the main index of sediment yield. The mean value of this index for a group of basins can be expressed by both the arithmetic mean and a weighted average calculated as the total sediment load from the group of basins divided by the total area of the basins. In this study we used the first value. The variability of sediment yield within the group of basins is expressed by an error term for the mean sediment yield given as a percentage. Bed load yields from the mountain regions on average comprise 23% of the suspended load.

For the analysis, we used basins with areas ranging from 500 to 100 000 $km^2$. In order to take account of the dependence of specific sediment yield on the area of the basin, data from small river basins and large river basins were treated separately. The dividing threshold was set at 5000 $km^2$.

Human activity in mountains results in forest destruction, cultivation of slopes, deterioration of grassland due to overgrazing, and the detrimental consequences of road building and construction of water storage reservoirs. However, the impact of human activity is not so important in influencing erosion as in lowland regions where the natural landscapes have been modified by man to a much greater degree. Nevertheless, the activities of man in mountain areas complicate the relationships between erosion and natural factors and the impact of human activity needs to be evaluated quantitatively. All the basins have been divided into three categories depending on the level of economic development. Characteristic indices for each of these categories (residual woodland and proportion of cultivated land) are given in Table 1.

Table 1 illustrates the strong impact of the economic use of a basin on the intensity of erosion. The analysis of the influence of natural factors on erosion and sediment yield in mountain areas has been undertaken by taking account of this factor. In general terms, we considered basins with a low degree of economic development (Category I) to represent natural landscapes. Based on this reconstruction of natural conditions, the sediment yields from mountain regions of the Earth as a whole can be seen to have increased by 1.4 times.

Reservoirs have been built on 60 of the rivers for which sediment yield data were available. On average, reservoirs cause a 50% reduction in sediment

**Table 1** Suspended sediment yields of mountain rivers (t km$^{-2}$ year$^{-1}$) according to the category of economic development.

| Degree of development | % Forest cover | % Cultivated land | Small rivers | | Large rivers | |
|---|---|---|---|---|---|---|
| | | | *N* | *s* | *N* | *s* |
| I low | 70 | 30 | 744 | 260 (0.4)* | 250 | 200 (0.7)* |
| II medium | 30-70 | 30-70 | 451 | 560 (0.6) | 141 | 290 (1.0) |
| III high | 30 | 70 | 136 | 680 (0.9) | 81 | 360 (1.8) |

*N* is the number of basins; $s$ = mean suspended sediment yield (t km$^{-2}$ year$^{-1}$).
*The error term (%) for the mean value is given in parentheses.

yield. We therefore excluded these rivers from the further analysis of controlling factors.

## EROSION AND RELIEF

Under natural conditions only slightly changed by man (basins of Category I) the intensity of erosion directly depends on the amplitude of relief. The economic activity of man, being different in different altitudinal zones, has, however, modified this simple dependence (Fig. 1).

A particularly marked increase in erosion is observed in low mountains, where economic activity has reached a high level. However, in intensely developed lowland areas erosion has increased to a still greater degree. This

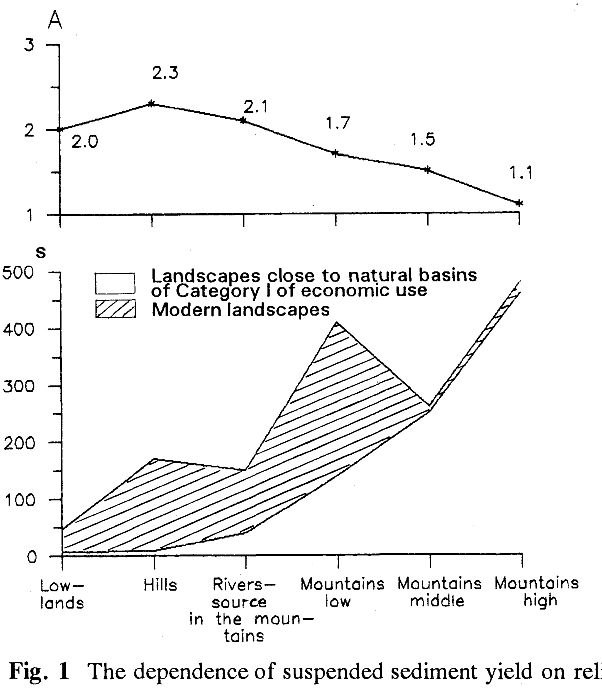


**Fig. 1** The dependence of suspended sediment yield on relief.

has led to a decrease in the difference in erosion intensity between mountains and plains. In landscapes that are completely natural or only slightly changed by man, erosion in mountain areas is 27 times greater than in lowland areas. In the case of anthropogenically changed landscapes, this increase reduces to 3.2 times.

Thanks to a greater preservation of the natural landscape, some mountain areas are less eroded than the adjoining densely populated plains. For example, sediment yields in the South and Middle Urals (up to 30 t $km^{-2}$ $year^{-1}$) are less than in the neighbouring eastern part of the Russian Plain (up to 200 t $km^{-2}$ $year^{-1}$).

Recent tectonic activity also influences the intensity of mountain denudation. Table 2 shows that with an increase of earthquake intensity by 1 point, the intensity of denudation in mountain areas increases almost twofold. However, one should bear in mind that the data presented in this Table also reflect the effect of mountain height, since higher mountains are usually characterized by increased seismic activity.

**Table 2** The relationship between seismic activity in mountain areas and suspended sediment yield (based on data from the USSR and adjoining territories).

| Intensity of earthquakes (points on the Richter scale) | $N$ | $s$ |
|---|---|---|
| 9 | 133 | 540 |
| 8-9 | 293 | 360 |
| 7-8 | 529 | 180 |
| 6-7 | 51 | 47 |
| 6 | 88 | 17 |

$N$ is the number of basins, $s$ = mean suspended sediment yield (t $km^{-2}$ $year^{-1}$).

## EROSION AND CLIMATE-LANDSCAPE CHARACTERISTICS

Climate and the resultant landscape characteristics influence erosion processes through two principal factors, namely, runoff and the degree of coverage of the surface by vegetation. Based on sediment yield data, the greatest mechanical denudation occurs in the glacial and subnival zones as well as in the subtropics in the Mediterranean zone (Fig. 2). All these mountain zones are characterized by limited protection of their soils by vegetation due to natural and anthropogenic (Mediterranean) factors. Runoff amounts are considerable here (1.5 or 2 times as great as the mean global value). Surface mechanical denudation is substantial, leading to a predominance of slope erosion over channel erosion.

In forest zones, erosion is weak with slope erosion being generally insignificant. All the processes of mechanical denudation are concentrated in the channels of rivers and on their banks. In forest zones, erosion intensity is closely related to runoff amount. Hence rivers in the tropics and subtropics evidence higher erosion rates than rivers in forest zones located in the

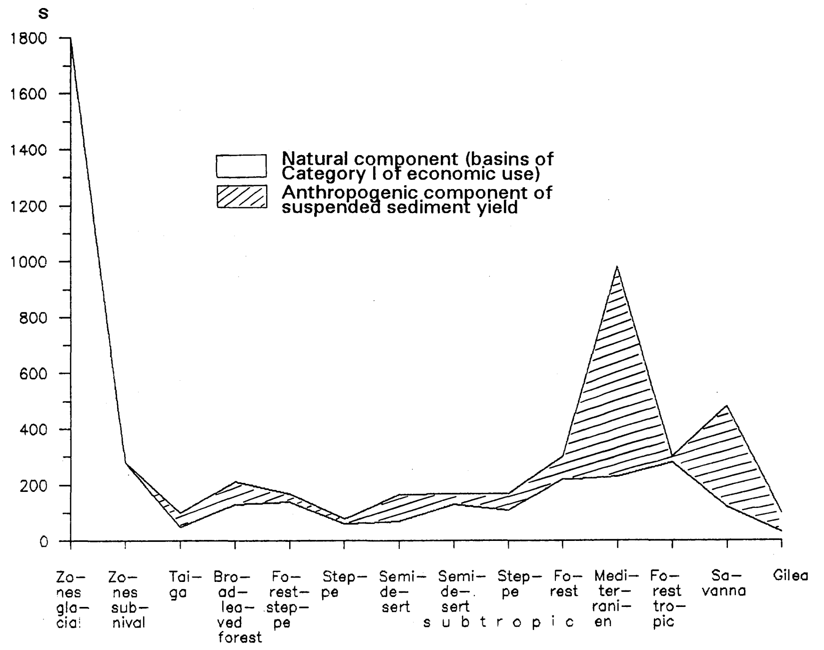


**Fig. 2** Suspended sediment yield ($s$, t km$^{-2}$ year$^{-1}$) in different landscape zones and belts of mountain regions.

temperate belt. There are only a few data for mountain rainforest areas, and these need to be checked. In the mountainous semi-deserts and steppes, erosion is insignificant due to the aridity of the climate and low runoff amounts.

It should be noted that for both mountains and plains, the rule of Langbein-Schumm (1958) which gives maximum erosion in semi-arid areas is not valid. Other researchers (Walling & Kleo, 1979; Jansson, 1988) have come to the same conclusion. In some measure this rule holds true where basin erosion depends primarily on the protective role of vegetation. For channel erosion, the dependence on vegetation is insignificant. The dependence of sediment yield on runoff in mountain areas is clearly evident, especially in basins with landscapes little changed by man.

## EROSION AND ROCK TYPE

In mountain areas, the influence of rock type generates the following sequence of sediment yield: loess ($s$ = 1800 t km$^{-2}$ year$^{-1}$), other terrigenic loose rocks (1300), coarse terrigenic rocks (550), metamorphic (420), limestones (310), igneous (100).

The selectivity of erosion in mountain areas is much greater than in plains areas. This feature is particularly prominent in mountain semi-deserts and in the Mediterranean (Dedkov & Moszherin, 1984), where tectonic structures occur. The weakest selectivity is characteristic of mountain forests in the temperate and tropical belts.

## THE COMBINED IMPACT OF DIFFERENT FACTORS

Various combinations of factors controlling erosion in mountain regions create conditions for intense erosion. The Pacific Asiatic-Australian sector evidences the most intensive erosion on the Earth. Based on data from 518 river basins in the mountain areas of this zone, the mean suspended sediment yield is 800 t $km^{-2}$ $year^{-1}$. Particularly intensive erosion occurs on the islands separated from the continents of Asia and Australia by ocean basins. In Taiwan a sediment yield of 31 700 t $km^{-2}$ $year^{-1}$ has been documented with background values of up to 5000 t $km^{-2}$ $year^{-1}$ (Li, 1976). Somewhat lower (11 000 or 12 000 t $km^{-2}$ $year^{-1}$) are the sediment yields reported for Java (Walling & Webb, 1983). In New Zealand, suspended sediment yields also reach high values - between 20 000 and 28 000 t $km^{-2}$ $year^{-1}$, with a mean value of about 2000 t $km^{-2}$ $year^{-1}$ (Adams, 1979).

The main reasons for such intense erosion throughout the whole sector are as follows: high precipitation amounts and intensities, high and irregular runoff (in New Zealand up to 280 l $s^{-1}$ $km^{-2}$), dissected mountain relief composed mainly of sedimentary rocks, intense recent tectonic activity, and replacement of forests by agricultural land in the low mountain areas.

The least intense erosion is found in the low mountains of the temperate zone that are mainly underlain by crystalline rocks and covered by dense forests (Scandinavia, Urals, the mountains of South Siberia, the Trans-Baikal region, etc.). In some locations within such regions, suspended sediment yields are only 10 or 20 t $km^{-2}$ $year^{-1}$.

## THE EROSIONAL SYSTEM AND ITS OPERATION

The complex of erosional processes operating in a river basin can be represented as an open dynamic system whose functioning is determined by the movement of water and sediment. Channel and slope erosion are the main elements of the system. Depending on the relative importance of these two elements, we may distinguish two types of system behaviour.

The first type is characterized by a predominance of channel erosion. It is common in forest areas with well preserved forest vegetation (basins of Category I). Slope erosion is minimal here. Erosional processes are mainly concentrated in river channels. The sediment yield of predominantly channel origin is proportional to runoff in basins of Category III (Makkaveev, 1955). That is why there is a downstream increase not only in sediment load but also in specific sediment yield. The specific sediment yield is positively related to basin area (Fig. 3(a)).

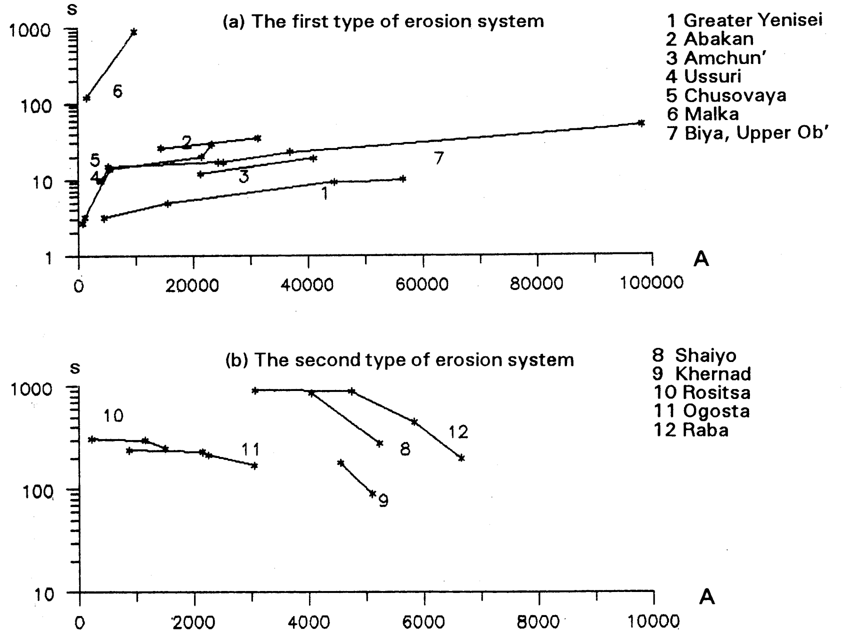


**Fig. 3** Dependence of specific sediment yield ($s$, t km$^{-2}$ year$^{-1}$) on basin area ($A$, km$^2$).

The second type of system is characterized by a predominance of slope (sheet, gully) erosion. It occurs in natural zones with a poor vegetation cover and with strong surface erosion and mechanical denudation (glacial, subnival, and semiarid zones). It is also common in forest zones with a high degree of economic development (basins of Category III and partly of Category II). Much of the denudation occurs in the upper parts of the river system. When moving down the rivers, part of the transported sediment accumulates in the channels and on the flood plains. This leads to a decrease of specific suspended sediment yield and to an inverse relationship between specific sediment yield and basin area.

The two types of erosional system behaviour are connected by a gradual transition. To produce a tentative quantitative estimate of the ratio of slope to channel erosion, we have developed and used a method based on an analysis of the dependence of suspended sediment transport on water discharge during low-water periods (Dedkov & Moszherin, 1984).

The form of the relationship between specific sediment yield and basin area is also a reliable index of the type of erosional system. A positive relationship is most common for the first type of behaviour and a negative relationship for the second. It is, however, important to take account of other factors influencing the relationship, particularly rock type, relief, and human activity (reservoirs etc.).

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