

## Continent-scale reservoir sedimentation patterns in the United States

**WILLIAM H. RENWICK**

*Department of Geography, Miami University, Oxford, Ohio 45056, USA*

**Abstract** Studies of spatial variability in sediment yield have focused on variations in climate, relief and lithology as the dominant controlling factors. Human-accelerated erosion complicates these relationships, and contributes to the tendency for streams to exhibit sediment delivery ratios considerably less than unity. This paper examines reservoir sedimentation data for the conterminous United States in relation to topography, climate and land use. The highest sediment yields and the greatest downstream decrease in specific sediment yield are associated with regions of greatest human impact on erosion. Spatial patterns of sediment yield and sediment delivery reflect human impacts (grazing and arable agriculture) and to a lesser extent natural physiographic conditions (climate and relief).

### INTRODUCTION

Geomorphologists have analysed sediment yield data sets encompassing a wide range of environments since the 1950s. The major theme of these analyses is the relationship between sediment yield and environmental conditions in the basin. Most studies identify climate, relief and lithology as the major independent variables.

Several studies relating climate to sediment yield have identified maxima in semiarid and Mediterranean climates (Langbein & Schumm, 1958; Dendy & Bolton, 1976; Judson & Ritter, 1964; Jansen & Painter, 1974; Saunders & Young, 1983; Inbar, 1992) and humid tropical and subtropical climates (Fournier, 1960; Wilson, 1973; Douglas, 1967; Jansson, 1988; Ohmori, 1983). However, Walling & Webb (1983) show that the specific relationships between climate and sediment yield are not consistent from one analysis to another, and that at the global level there is no consistent pattern relating the two variables.

Correlations between relief or geological characteristics and sediment yield have also been demonstrated both at the global scale and within specific regions (Jansen & Painter, 1974; Judson & Ritter, 1964; Ahnert, 1970). The areas of highest sediment yield are those that combine erodible materials such as loess with moderate to high relief as in east-central Asia (Milliman *et al.*, 1987).

A second theme that characterizes studies of sediment yield is a negative relationship between sediment yield per unit drainage area, or specific sediment yield, and drainage area. The relationship is a manifestation of sediment delivery ratios considerably less than unity, and is observed in many sediment yield data sets (Walling, 1983). Typically the relationship is such that a ten-fold increase in drainage area is associated with a decrease in specific sediment yield of 10-40%. The lack of clear linkage between erosion and sediment yield calls into question interpretations of spatial variations in erosion rates based on sediment yield data (Trimble, 1975).

One cause of the negative specific sediment yield-drainage area relationship may be the tendency for material eroded from uplands to accumulate in valley fills on a long-term basis due to topographic differences between large and small basins (Chorley *et al.*, 1984). Such topographic factors include higher relief in small basins, greater flood plain area in large basins, and differences in relative flood magnitudes. However, the high rates of sediment accumulation in colluvial and alluvial deposits implied by sediment yield data probably cannot be sustained for long periods of time.

Alternatively, the form of the specific sediment yield-drainage area relationship may reflect the pulse of sediment that has entered many drainage systems in the past few hundred years as a result of human activity (Meade & Trimble, 1974; Costa, 1975). A dramatic increase in upland erosion has occurred in most of the Earth's populated areas (in which the bulk of these data have been gathered) and studies of sediment budgets in human-impacted areas demonstrate that most of the added sediment remains in the upstream portions of catchments and is being slowly transferred downstream. The magnitude of the human impact on sediment yield is so great that in many areas it dwarfs the effects of physiographic variables (Douglas, 1967).

In contrast to the general trend, a few areas have been shown to exhibit rough equivalence of specific sediment yield in large and small basins, or an increase in specific sediment yield downstream. One such work (Reneau & Dietrich, 1991) covers a time-span of thousands of years and thus is not affected by recent human impacts, while another (Church & Slaymaker, 1989) studies basins relatively free from human activity.

This paper re-examines sediment yield data from reservoir surveys for the conterminous United States that have previously been interpreted primarily in relation to climate and physiography. Specifically, it will describe regional patterns and interpret broad environmental controls on: (a) average sedimentation rates; and (b) the specific sediment yield-drainage area relationship. It will be argued that the spatial patterns of sediment yield and sediment delivery are controlled by a combination of land use history and climatic/physiographic characteristics, rather than by climate and physiography alone.

## DATA AND METHODS

While modern sediment yields can be measured directly, either through water sampling or reservoir sedimentation, the latter provides relatively good estimates of average sediment yields over periods of years to decades for a large number of basins. Measurement errors associated with trap efficiency variation can be a problem, but this is more than offset by the benefits of long periods of record and the large number of measurements available. The most important source of bias in reservoir sediment data is that reservoirs with high sedimentation rates are more likely to be surveyed than those with low rates. Also, in the United States, agricultural regions tend to have more small reservoirs than non-agricultural regions, and there is hence a smaller average drainage area associated with data from agricultural regions in comparison to non-agricultural areas.

The sediment yield data used here were taken from a compilation of sediment surveys published by the US Department of Agriculture (Dendy & Champion, 1978). This compilation includes over 3000 sediment surveys of 1609 reservoirs. These surveys

were conducted prior to 1975 by various government agencies, and form the most complete set of reservoir sedimentation data currently available for the United States. After the mid-1970s government-sponsored sediment data collection declined significantly, and a centralized compilation of surveys since 1975 is not yet available. Dendy & Champion (1978) report sedimentation rates as volumes for all reservoirs; bulk densities are provided for some, but not most of the surveys. Trap efficiencies are not available. For these reasons volumetric rather than mass-based sediment yield data were used in this study. The data base includes both total drainage area and contributing drainage area. The latter excludes portions of a basin from which sediment is captured by upstream reservoirs. Contributing drainage area was used in this study. Drainage areas range from  $10^{-2}$  to  $10^5$  km<sup>2</sup> and average 1400 km<sup>2</sup>.

Dendy & Champion (1978) report locations of reservoirs by water resource region, county, and by the name of the nearest town. The location of the nearest town is used as a surrogate for reservoir location in this study. The  $7.62 \times 10^6$  km<sup>2</sup> study area includes about 18 000 named places. Thus for most reservoirs, particularly in the more densely-populated central and eastern US, locations are accurate to within about 20 km; in western regions reservoir locations may only be accurate to within about 50 km. It was possible to determine locations for 1551 reservoirs, and the average length of record is 19 years.

Land use data were taken from the 1982 National Resource Inventory compiled by the United States Department of Agriculture (USDA, 1995). These data are collected at 5-year intervals through sampling of land surface characteristics. Major land resource areas (MLRAs) are the first level of generalization of these data. MLRAs are regions that have distinctive soil, climate, water resource, and land use characteristics (USDA, 1981). The study area includes 181 MLRAs, averaging 43 000 km<sup>2</sup> in area, of which 133 are represented by reservoirs in the sedimentation data set. These MLRAs are further grouped into 20 Land Resource Regions (LRRs) which are roughly similar to physiographic regions. MLRAs and LRRs differ from previous physiographic maps in that land use is a major factor in defining regions.

Climatic data were extracted from 1 km resolution raster maps of mean annual precipitation ( $P$ ) and mean annual potential evapotranspiration ( $PE$ ), calculated using the Thornthwaite method. The average precipitation and  $PE$  in a circle of 5 km radius centred on the town nearest the reservoir site was determined.  $P - PE$  is used as an index of the humidity or aridity of climate in this study.

Topographic data were derived from 3-second digital elevation data obtained from the US Geologic Survey. These data consist of spot elevations on a 3 arc-second grid. The data set was reduced in size by a factor of 100 by determining the total relief in each 30-second by 30-second rectangle (about 0.73 km<sup>2</sup> at 35° latitude). This map was then projected to Lambert's Conformal Conic projection and re-sampled at 1 km resolution. Local relief in the vicinity of a reservoir was determined by calculating the average value of local relief within a 5 km radius of the town nearest the reservoir. Because drainage basin boundaries were not available, relief could not be estimated for entire basins.

Topographic, climatic and land use data were analysed at two scales: individual reservoirs and Land Resource Regions. Correlation and regression were used to examine the effects of drainage area, topography, climate and land use on specific sediment yield for individual reservoirs (specific sediment yield and drainage area were log-

transformed). Land use data were not available at the individual reservoir scale; MLRA averages were used. At the LRR scale the relationships between sediment yield and topographic, land use and climatic characteristics were examined within each region. Regions with fewer than 15 reservoirs were omitted from the analysis. This resulted in recognition of 15 regions, data from which were used in this analysis. These regions were further generalized into four major landscape groups.

## RESULTS

Sedimentation rates vary through four orders of magnitude, with higher rates tending to occur in smaller drainage areas (Fig. 1). The causes of this variability are, however, not distinguishable at this scale of analysis. Of the four independent variables examined (drainage area, local relief,  $P - PE$  and percent crop land in the MLRA) drainage area has the strongest effect on specific sediment yield (Table 1). Percent crop land has a weak positive effect on specific sediment yield. A weak but statistically significant negative effect of relief on specific sediment yield is a spurious consequence of the strong negative correlation between crop land and relief. A negative correlation between crop land and drainage area indicates a bias in the data toward small drainage basins in agricultural regions.

Regional analyses show considerable spatial variation in sediment yield (Fig. 2; Table 2). Specific sediment yield is highest in the agricultural regions of the humid eastern and central states, and in the Coast Ranges of California. Moderate sediment yields occur in the western Great Plains, the semiarid western states, and in the Appalachians. Low values occur in forested areas of the northeast and northwest, and in the northern Great Plains. With the exception of the Coast Ranges, neither the areas of highest relief (the Rocky Mountains and the Cascades/Sierras) nor the areas of

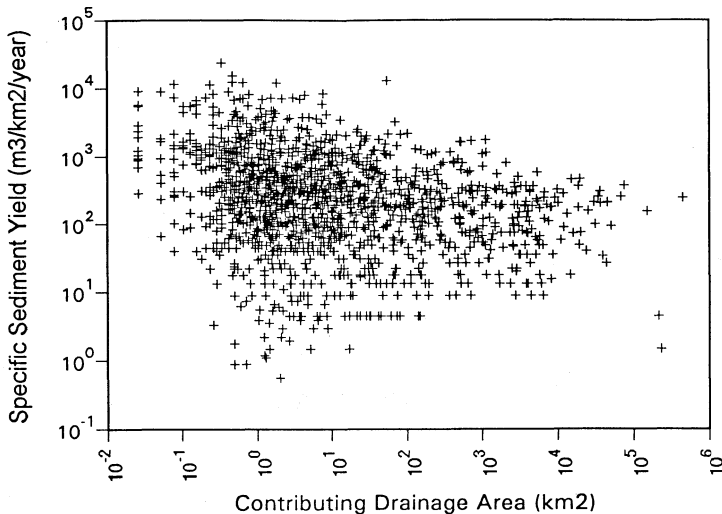


Fig. 1 The relationship between specific sediment yield and contributing drainage area for all data used in the study.

**Table 1** Correlation matrix of sedimentation rates and environmental characteristics using individual reservoir data.

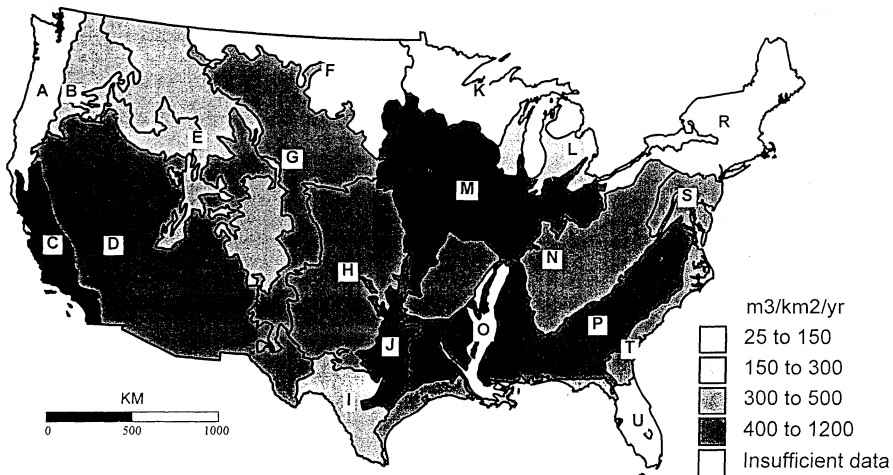
	log <i>SY</i>	log <i>DA</i>	Relief	<i>P</i> - <i>PE</i>	% Crop
Log specific sediment yield	1.00	<u>-0.27</u>	-0.07	0.00	<u>+0.09</u>
Log contributing drainage area	<u>-0.27</u>	1.00	-0.01	<u>+0.10</u>	<u>-0.11</u>
Local relief	-0.07	-0.01	1.00	-0.03	<u>-0.45</u>
Precipitation - <i>PE</i>	0.00	+0.10	-0.03	1.00	<u>+0.23</u>
Percent crop land (MLRA)	<u>+0.09</u>	<u>-0.11</u>	<u>-0.45</u>	<u>+0.23</u>	1.00

*N* = 1551; **bold** indicates significant at  $p < 0.05$ ; underline indicates significant at  $p < 0.01$ .

semiarid climate (intermontane basins and western Great Plains) have especially high average sediment yields.

The slope of the log drainage area-log specific sediment yield relationship is similarly quite variable. In the Appalachian mountains and Piedmont (Regions N and P), the intensely agricultural north-central states (Region M) and in the semiarid west (Regions B, C and D), drainage area has a strong negative effect on specific sediment yield. In the western mountains, the wheat-growing regions of the Great Plains, and in the northeastern forests there is little or no downstream decrease in specific sediment yield.

Aggregation of data at the LRR level allows an evaluation of the relationships between physiographic characteristics and sediment yield (Figs 3 and 4). Local relief has no apparent effect on specific sediment yield; with the exception of the California Coast Ranges (Region C) the regions with the highest sedimentation rates have relatively low local relief. The plot of specific sediment yield in relation to  $P - PE$  does show a tendency for higher yields in areas of semiarid climate, with lower yields in very arid and humid regions.

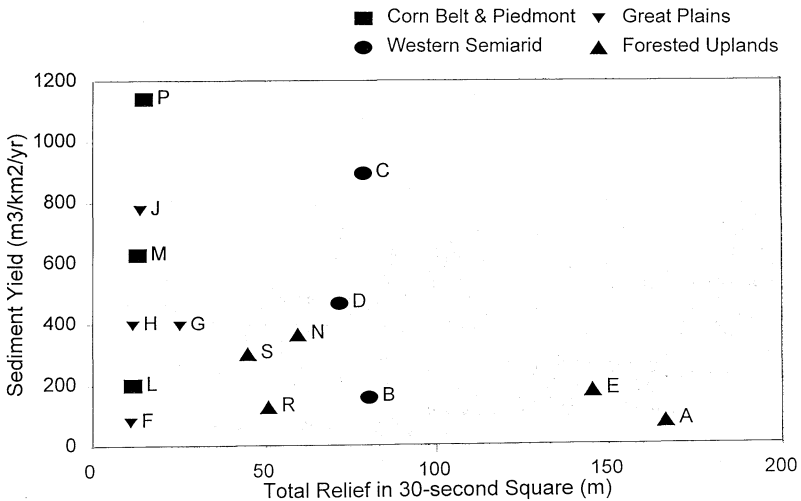
**Fig. 2** Map of average specific sediment yield for individual land resource regions.

**Table 2** Specific sediment yield, environmental characteristics, and slope of the log specific sediment yield-log drainage area relationship for individual land resource region.

Land Resource Region	Landscape group	Average specific sediment yield (m <sup>3</sup> km <sup>-2</sup> year <sup>-1</sup> )	Average local relief (m)	Percent crop land	Log SY – log DA slope	Number of reservoirs
A	Forested mountains and uplands	80	166	3	+0.17	19
E		180	146	4	+0.06	61
R		131	51	10	-0.13	44
N		367	60	11	<b>-0.39</b>	150
S		305	45	23	-0.06	33
B	Western semiarid	160	80	25	<b>-0.42</b>	56
C		896	79	25	<b>-0.28</b>	172
D		469	72	2	<b>-0.25</b>	173
F	Great Plains	80	11	56	-0.10	36
H		398	12	46	<b>-0.17</b>	210
G		397	25	14	<b>-0.34</b>	46
J		777	14	19	<b>-0.23</b>	81
L	Corn belt and piedmont	200	11	49	<b>-0.65</b>	19
M		628	13	63	<b>-0.52</b>	322
P		1141	15	17	<b>-0.63</b>	104

Regions with fewer than 15 reservoirs were omitted from regional analyses; **bold** indicates correlations significant at  $p < 0.05$ ; **underline** indicates significance at  $p < 0.01$ .

Sediment delivery, as indicated by the slope of the specific sediment yield-drainage area relationship, is affected by physiography and land use. Sediment delivery is high in high-relief areas, especially western mountain regions (Regions A and E), although land use is also significant (Fig. 5). Regions that have seen large increases in erosion rates since European occupation (especially Regions C, D, L, M and P) have lower



**Fig. 3** The relationship between specific sediment yield and local relief, aggregated by Land Resource Region. (Regions are identified in Table 2 and Fig. 2.)

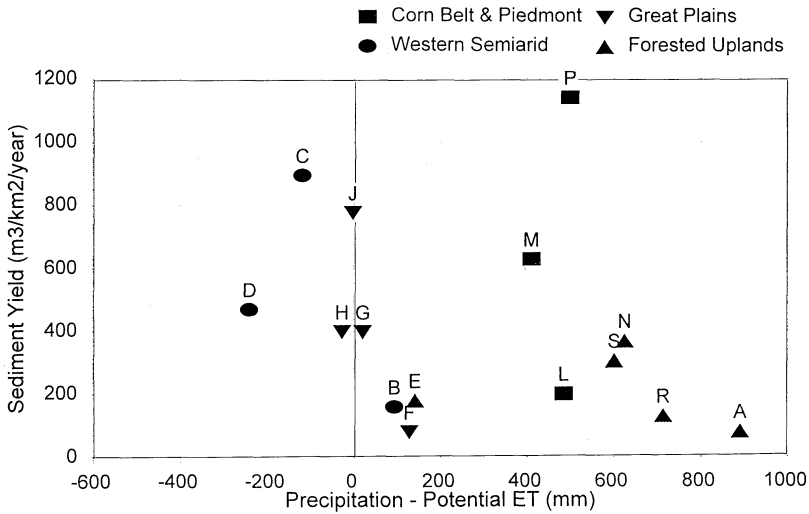


Fig. 4 The relationship between specific sediment yield and precipitation – potential evapotranspiration, aggregated by Land Resource Region.

sediment delivery than less-impacted regions of similar relief. The general negative relationship between crop land and sediment delivery is evident in Fig. 6.

### DISCUSSION AND CONCLUSIONS

Two trends emerge from these results. First, correlations between specific sediment yield and physiographic characteristics (relief, climate) are weak at best. Although there are sound physical bases for the beliefs that semiarid climate and/or high relief should

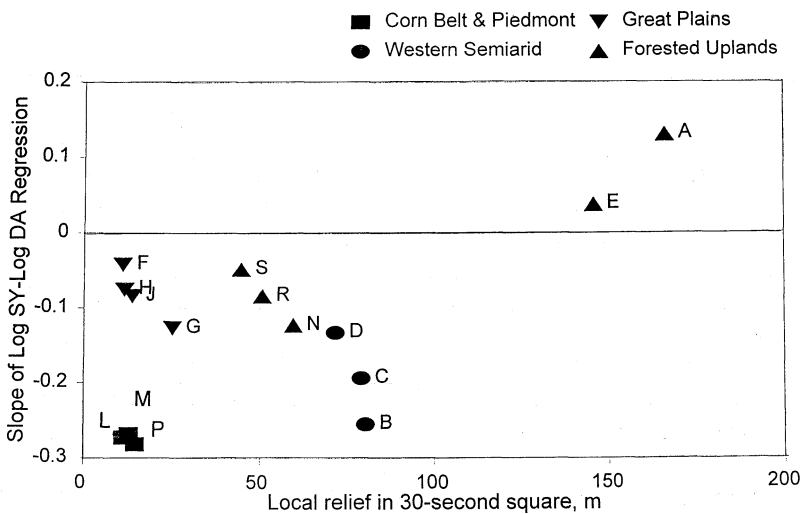
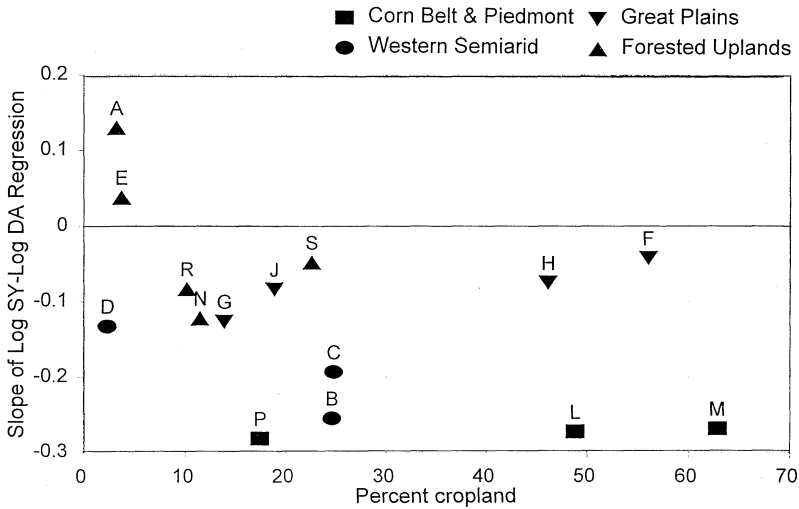


Fig. 5 The relationship between sediment delivery and local relief, aggregated by Land Resource Region.



**Fig. 6** The relationship between sediment delivery and percent crop land, aggregated by Land Resource Region.

correspond to higher sediment yields, the data examined here do not support those generalizations. The Coast Ranges of California which have high relief, a semiarid climate, and high sedimentation are the only region in this analysis that conforms to the rule. Second, the intensity of agricultural land use, especially in humid areas, has a profound impact on both the magnitude of sediment yield and the relationship between specific sediment yield and drainage area. The highest sediment yields and the greatest effect of drainage area on specific sediment yield are found in humid agricultural regions.

When human and natural physiographic factors are considered together, the 15 land resource regions for which sufficient data are available can be grouped into four landscape types, as follows:

(a) **Forested mountains and uplands** (Regions A, E, N, R and S) have relatively low sediment yields and little or no decrease in specific sediment yield with increasing drainage area. Regions A and E have particularly high relief and no apparent loss of sediment downstream, while regions N, R and S have moderate relief and a very small downstream decrease in specific sediment yield. These are areas of predominantly forest vegetation and relatively little agriculture. Although there has been an increase in erosion in the period of European occupation, the lack of significant downstream decrease in specific sediment yield suggests either that the increase in upstream sediment input is small, or that the sediment delivery system is relatively efficient. This is consistent with the findings of Reneau & Dietrich (1991), whose study area is in this region (A). The high relief and narrow valley bottoms characterizing these regions would tend to favour fluvial sediment transport and limit temporary storage.

(b) The **semiarid uplands** of the western US (regions B, C and D) have moderate to high relief, low to moderate amounts of crop land, and generally large downstream decreases in specific sediment yield. Even though these regions are not extensively



cropped, they have seen a significant increase in erosion, both on uplands and in small tributaries, since European occupation (Cooke & Reeves, 1976). The ephemeral nature of stream flow promotes deposition in alluvial fans and inefficient sediment delivery (Hadley & Shown, 1975).

(c) The **Great Plains** include both regions that are principally range lands (G and J) and intensively cropped regions (F and H). The entire region has low relief, though range lands tend to have slightly more relief than crop lands. Although this region is used intensively for animal and plant agriculture, water erosion rates on crop land are lower than in more humid areas to the east. The region thus has only a modest downstream decrease in specific sediment yield.

(d) The regions in the eastern US most affected by accelerated erosion are the **Corn Belt** of the midwest (L and M) and the **Piedmont** region on the eastern slope of the Appalachians (P). The Corn Belt has 50-65% of its area in crops, and while the Piedmont today is only about 17% cropped it was much more intensively farmed in the eighteenth and nineteenth centuries and suffered severe erosion. Relief in these regions is low, yet they have the highest rates of soil erosion on crop land, primarily because of the humid climate. Sediment yields are moderate to high, and there is a large decrease in specific sediment yield with increasing drainage area.

In summary, based on an analysis of sedimentation rates in 1551 reservoirs in the mid-twentieth century, the spatial patterns of sediment yield in the conterminous United States are a consequence of both natural features and human modification of the landscape. The regions with highest sediment yields include heavily modified landscapes such as crop lands in the eastern states, and those with naturally high erosion, such as the Coast Ranges of California. A decrease in specific sediment yield with increasing drainage area is not universal; rather it is most evident in regions where the human impact on source-area erosion has been greatest, and it is least evident in high relief forested areas in which human impact has been less severe. Human impact appears to be much more significant in controlling spatial patterns of sediment yield than natural factors.

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