GENESIS OF SEDIMENTS: THE DRIVING FORCES

HAY, W.W., GEOMAR, Christian-Albrechts-University, Kiel, Germany

Summary

The ultimate control on erosion is the rate at which rocks are weathered and transformed into solutes and particles small enough to be transported. Weathering is dependent on temperature, availability of moisture, plant cover and relief. Three agents, rivers, glaciers, and winds, transport detrital sediment from land to the sea by, whilst only rivers and groundwater carry the dissolved material. The shoreline is an arbitrary boundary within the detrital sediment transport system, which extends from a site of origin across areas of temporary storage to a site of long-term deposition. The most important of the agents moving sediment across the land is river transport, estimated to be in the order of 20 x 1012 kg of sediment annually at present. Analysis of drainage basins indicates that relief and runoff are the most important factors in determining the detrital sediment load of rivers. The geology of the drainage basin is the most important factor controlling the dissolved load. The competence of rivers to transport detrital sediment is governed by the volume flow, gradient, and the sediment load itself, whereas the dissolved load is largely unaffected by these factors. Today, most large rivers are fed by snowmelt in highland areas, runoff from rainfall in the drainage basin, and groundwater inflow. Along the river course, water is lost to evaporation and groundwater infiltration, particularly affecting the transport of the detrital load. Detailed understanding of these processes through time will require integration of climate, soil development, and transport models.

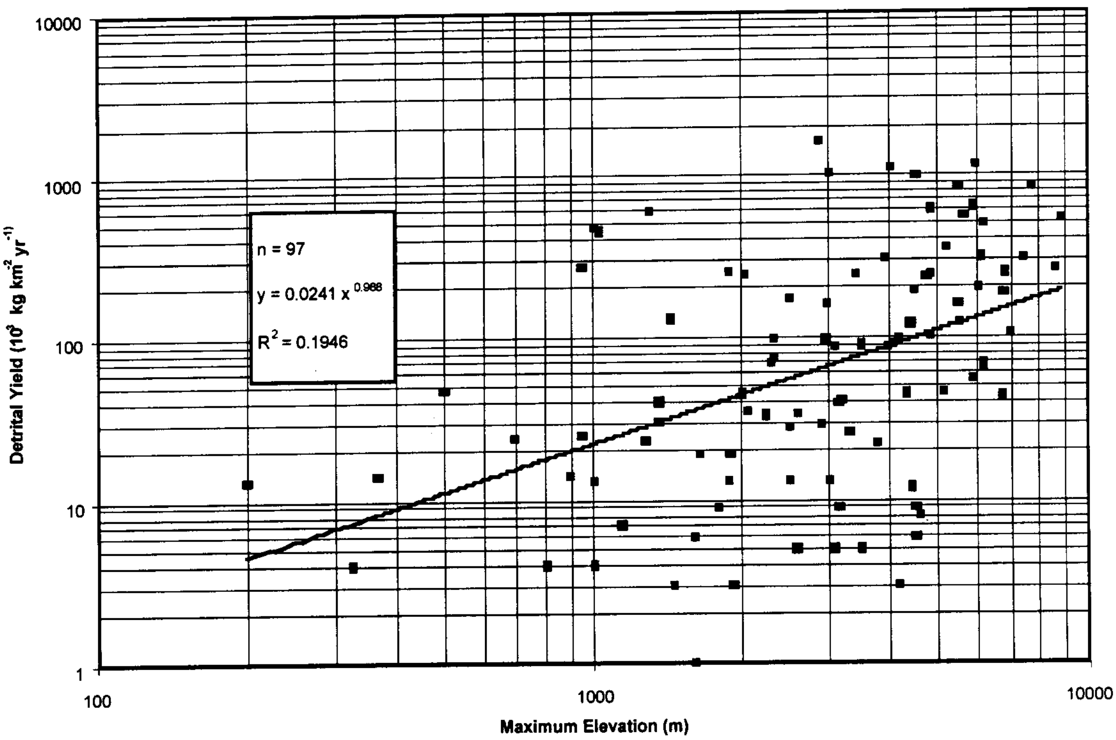
Weathering - The Ultimate Limit on Erosion Rates

The temperature changes responsible for mechanical weathering occur between day and night in desert regions and between the seasons at high latitudes and altitudes. Variations in temperature are greatly reduced by a mantle of soil; diurnal changes penetrate only a few centimeters, and seasonal changes little more than a meter. Mechanical weathering also Chemical weathering results from rainfall and atmospheric gasses reacting with the mineral constituents of rocks. The three main forms of chemical weathering are hydrolysis, oxidation, and the carbonation reaction. The temperature and availability of water, as well as the nature of the material being altered limit the rates of these processes.

The Detrital Sediment Yield

The detrital sediment yield from a drainage basin is the mass or thickness eroded per unit time. Although detritus may be stored temporarily in flood plains, on geologic time scales, erosion in the source area must equal deposition in the sinks. Hay (1998) concluded that the major controls on detrital

Fig. 1. Relation between detrital sediment yield and maximum elevation in the drainage basin for 97 rivers. Data from the Oxford Global Sediment Flux Database (Allen, 1997).

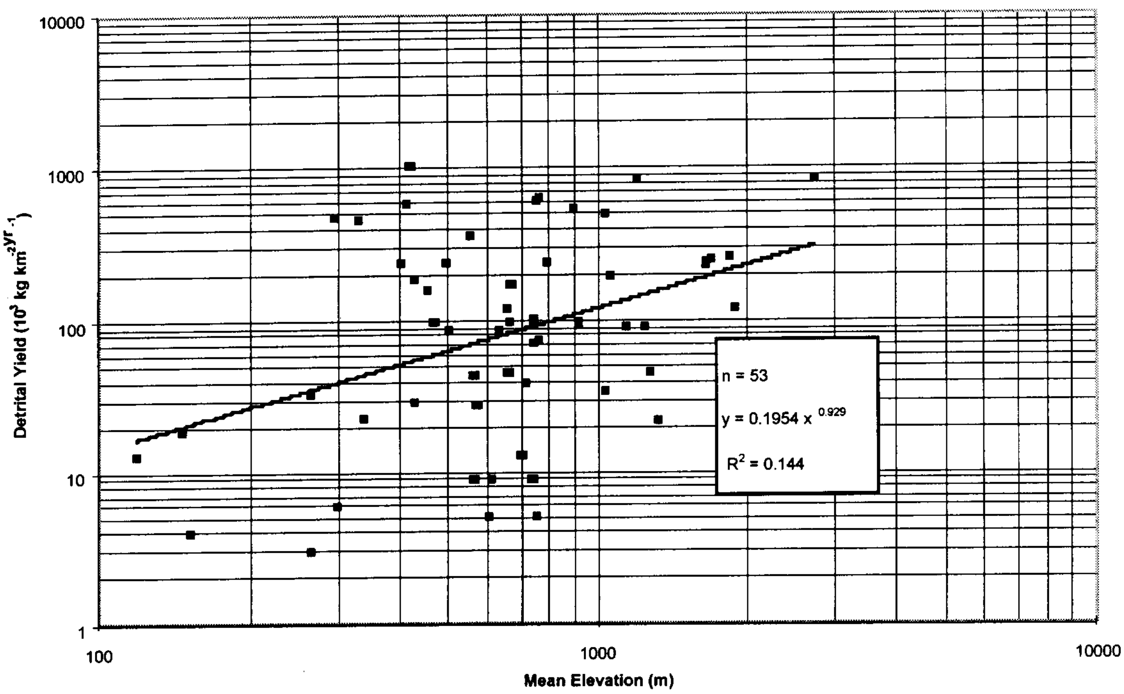


yields are geology, elevation, and climate. In large basins, the geology is varied and the relative susceptibilities of different lithologies to erosion average out; hence the details of the geology are usually neglected.

Relief: Many studies indicate that the relief of the drainage basin is the dominant factor affecting the sediment yield and denudation rate (Figs. 1,2,3). Intuitively, the most obvious relation should be between detrital sediment yield and the slopes of mountain- and hillsides (local relief). For many drainage basins data on local relief were not available until recently, older studies were based on the maximum (Fig. 1), the mean (Fig. 2) elevation in the drainage basin, or the basin relief, which is the difference between the highest and lowest elevations in the basin. Another measure that has been used is the relief/length ratio, which is the basin relief divided by the (greatest) length of the basin (Fig. 3).

Fig. 2. Relation between detrital sediment yield and mean elevation in the drainage basin for 53 rivers. Data from the Oxford Global Sediment Flux Database (Allen, 1997).

between sediment loads and climatic factors have been elusive. In a classic, frequently cited study, Langbein and Schumm (1958) found that erosion rates are highest where rainfall is low (< 25 cm/yr), in the region between savanna grasslands and shrub deserts where plant cover is discontinuous and soil material is readily mobilized by intermittent rainwater. This has come to be termed the Langbein-Schumm Rule. It became evident that low annual rainfall amounts were important, but its irregular distribution. Corbel (1959) demonstrated that areas with strong seasonal variations of rainfall have higher denudation rates than regions where the precipitation is more evenly distributed throughout the year. An alternation of wet and dry seasons promotes changes in the vegetation that make it easier for the sudden onset of rainy conditions to erode soils. Fournier (1960) tried to quantify the irregularity of the rainfall by dividing the square of the rainfall amount during the month with highest precipitation by the total annual rainfall. This ratio has subsequently become known as the Fournier index (Fig. 4). Schumm (1965) found that the peak



The relations between these relief parameters and sediment yields are empirical, but a variety of mathematical expressions have been developed to describe them. There is much scatter in the data on detrital sediment yields, and the correlation coefficients are always lower for larger data sets. Curiously, the best correlations are with the simplest parameter, the basin relief. Correlation coefficients decline as the relief parameters become more complex.

Climate: Although it is often stated that there is a relation between erosion rates and climate, quantitative relations

of sediment yield occurs at higher amounts of annual precipitation as the annual temperature increases. He concluded that this is because evaporation and transpiration usually increase more rapidly than precipitation at higher temperatures, so that less moisture is available to form plant cover and to become runoff. Hay et al. (1987, 1989) noted that Arctic rivers, emptying into the sea in regions where the mean annual temperature is well below 0° C, have anomalously low

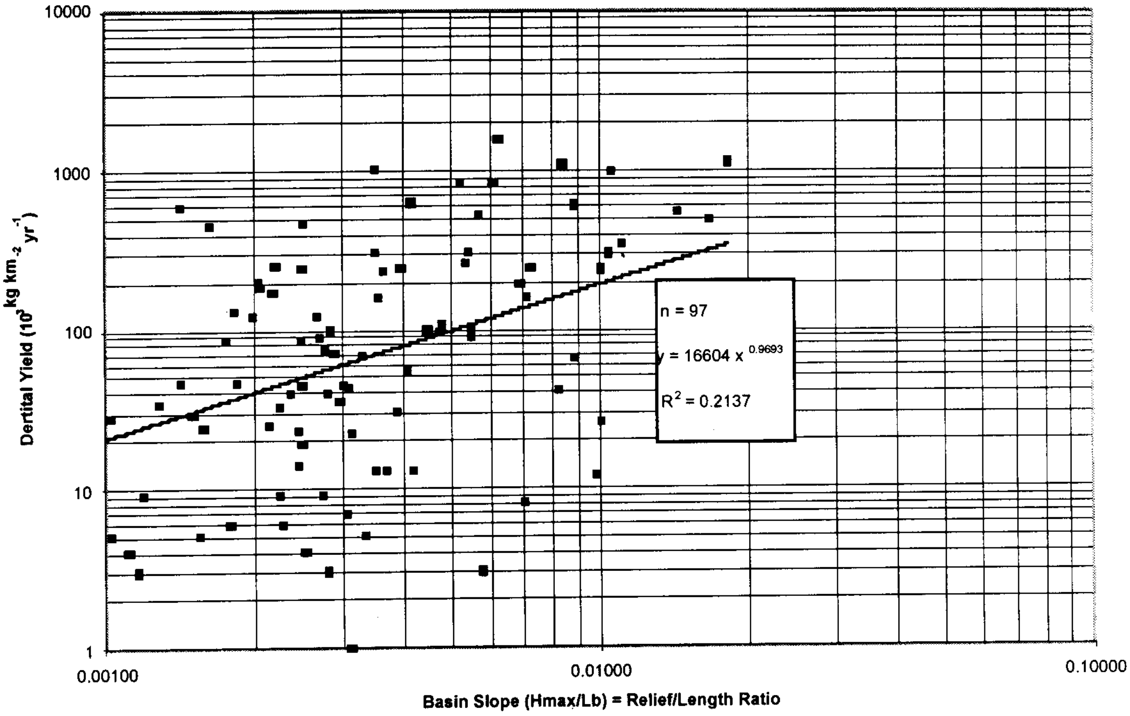
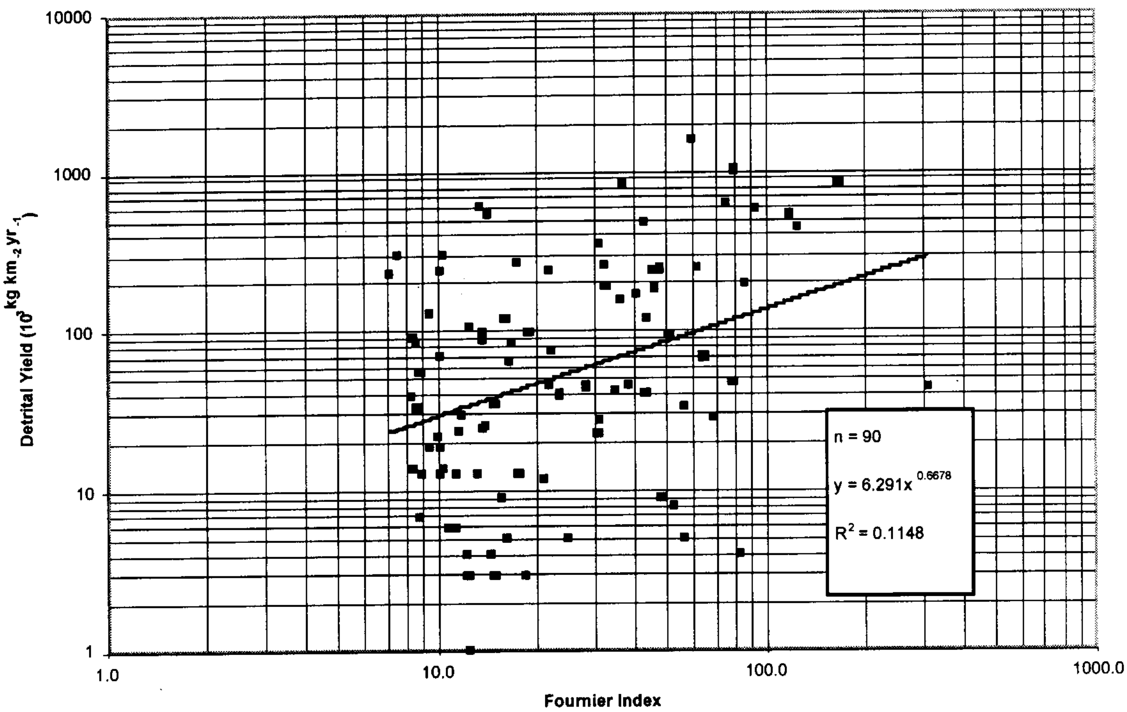


Fig. 3. (above) Relation between detrital sediment yield and basin slope for 97 rivers. Data from the Oxford Global Sediment Flux Database (Allen, 1997).

sediment loads. They attributed this to permafrost and to their short periods of flow in the arctic summer. Recently, Ludwig et al. (1998) have suggested that seasonality of rainfall may be as important in controlling detrital sediment flux as relief.

Fig. 4. (below) Relation between detrital sediment yield and the seasonality of runoff as expressed by the Fournier Index. Data from the Oxford Global Sediment Flux Database (Allen, 1997).



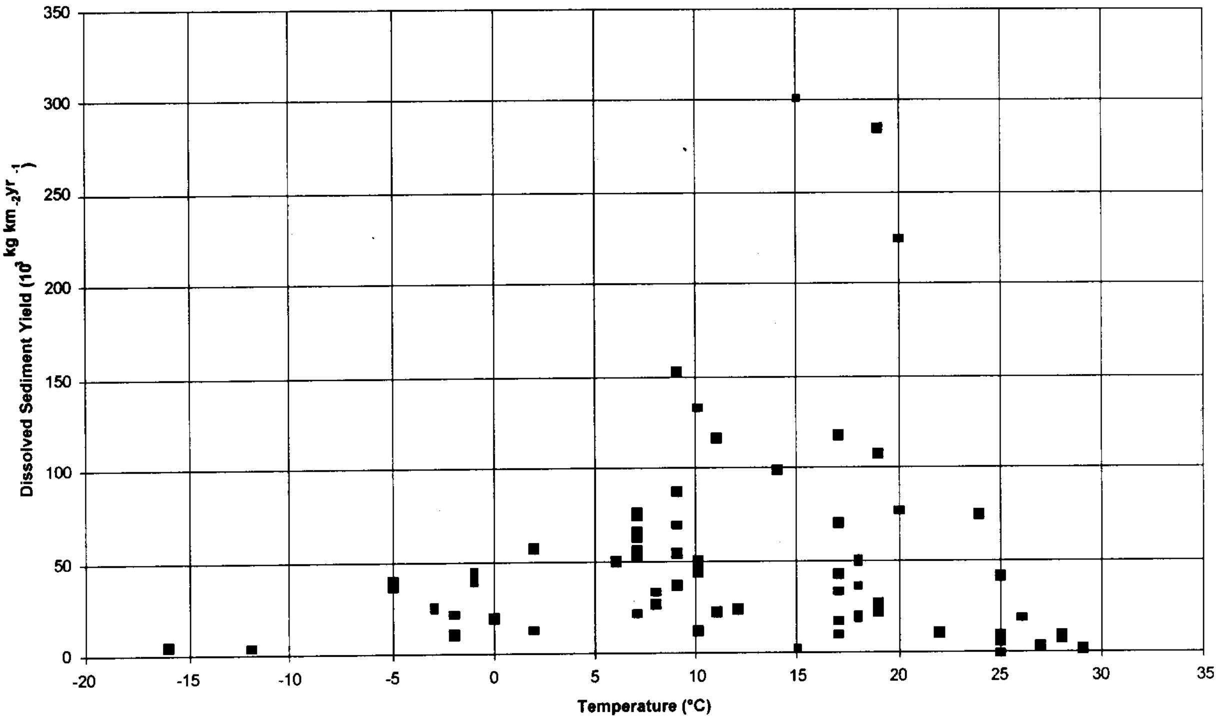


Fig. 5. Relation between dissolved sediment yield and temperature. After data in the Oxford Global Sediment Flux Database (Allen, 1997).

The Dissolved Sediment Load

The dissolved sediment load is largely dependant on the rate of weathering of rock in the drainage basin. Chemical weathering rates should be a function of temperature, the availability of water, and the nature of the rocks at and near the surface. The susceptibility of different rocks to dissolution plays an important role. The presence of easily dissolved rocks, such as evaporites or carbonates, within the drainage basin is one of the most important factors governing the chemistry of rivers. In general the concentration of solutes in river water is inversely proportional to the runoff.

As shown in Fig. 5 the relation with temperature shows much scatter. The decrease in dissolved load at warm temperatures may be the tropical weathering effect, i.e. much of the soluble material has already been removed.

Summary

Although it is evident that the detrital loads of rivers are related to the relief of the drainage basin and to the seasonality of rainfall in the basin, there is great variability in the data. Similarly, the dissolved loads are related to the temperature and availability of water, but the data show much scatter. There is little information on the role of extreme events, such as hundred or thousand year floods on sediment transport. The scatter is due in part to recent climatic changes associated with the transition from the last glacial to the Holocene, and to human activities which have affected most watersheds for hundreds to thousands of years. Better understanding of erosional processes may come from observation of sediment transport integrated over longer-term intervals.

References

Allen, P. A. 1997. Earth Surface Processes. Oxford, UK, Blackwell Science.

Corbel, J., 1959. Vitesse de l'érosion. Zeitschrift für Geomorphologie, 3: 1-28.

Fournier, F., 1960. Climat et Érosion. Presses Universitaires de France, Paris, 201 pp.

Hay, W.W., Rosol, M.J., Jory, D.E., and Sloan, J.L., II, 1987. Tectonic control of global patterns of detrital and carbonate sedimentation. In: L.J. Doyle, and H.H. Roberts (Editors), Carbonate Clastic Transitions: Developments in Sedimentology, v. 42. Elsevier, Amsterdam, 1-34.

Hay, W. W., C. A. Shaw, et al. 1989. "Mass-balanced paleogeographic reconstructions." Geologische Rundschau **78**: 207-242.

Hay, W. W. 1998. "Detrital sediment fluxes from continents to oceans." Chemical Geology **145**: 287-323.

Langbein, W.B., and Schumm, S.A., 1958. Yield of sediment in relation to mean annual precipitation. EOS Transactions of the American Geophysical Union, 39: 1076-1084.

Ludwig, W., J.-L. Probst, et al. 1996. "Predicting the oceanic input of organic carbon by continental erosion." Global Biogeochemical Cycles **10**: 23-41.

Schumm, S.A., 1965. Quaternary paleohydrology. In: H.E. Wright, Jr., and D.G. Frey (Editors), The Quaternary of the United States. Princeton University Press, Princeton, NJ, 783-794.