*Erosion, Transport and Deposition Processes* (Proceedings of the Jerusalem Workshop, March-April 1987). IAHS Publ. no. 189, 1990.

# The relationship between sediment delivery ratio and stream order: a Romanian case study

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**Abstract** An investigation of sediment delivery ratios in three regions of Romania (Moldavian Tableland, Subcarpathians and Flysch Mountains) shows a inverse relationship between sediment delivery ratio and drainage basin order (Strahler's system). However, these relationships vary in their precise form. There are two main controlling factors, namely, rock erodibility and runoff regime. When the rocks are easily eroded and the small headwater catchments evidence runoff of torrential character, the sediment delivery ratio decreases markedly with an increase in river network order. This is the case in the Moldavian Tableland, where the foot hills are a zone of active colluviation. When the rocks are easily eroded, but the runoff is greater, high sediment delivery ratios exist. This is the case in the Subcarpathians. When the rocks are resistant to erosion and the runoff is also high, the relationship between sediment delivery ratio and drainage basin order exhibits a more moderate slope, as shown by the Flysch Mountains.

## INTRODUCTION

An investigation of the relationship between sediment delivery ratio (SDR) and drainage basin order (Strahler's system) has been undertaken for three areas of Romania, namely, the Moldavian Tableland, the Subcarpathians and the Flysch Mountains. The last two areas, are represented by the basin of the Putna River in the Vrancea region (Fig. 1). The slope erosion was designated the *effective erosion* ($E_v$ t km$^{-2}$ year$^{-1}$) and the *specific rate of sediment transfer* ($E_s$ t km$^{-2}$ year$^{-1}$) was estimated from measurements of sediment load at river cross sections. $E_s$ therefore also represents the *sediment yield*. In the areas in which slope erosion is primarily the result of surface erosion, the distinction between effective erosion and sediment yield is clear. On the contrary, in areas in which sediment production from the slopes is mainly the result of mass movements (landslides, mud flows, creep) only loosely connected with fluvial processes, the distinction is less clear. In these cases, it is better to think in terms of *gross erosion* which is defined as the sum of inter-rill, rill, gully and channel erosion in small catchments. The sediment delivery ratio represents the ratio between the effective erosion or the gross erosion and the sediment yield.

In the cases studied, *effective erosion* was employed for the Moldavian Tableland, where the main sediment sources from the slopes are associated with surface erosion. For the Flysch Mountains and Subcarpathians areas, *gross erosion*, representing the sediment yields for basins of order I and II respectively (Ichim & Radoane, 1986), was used. These basins are smaller than 1 $km^2$.

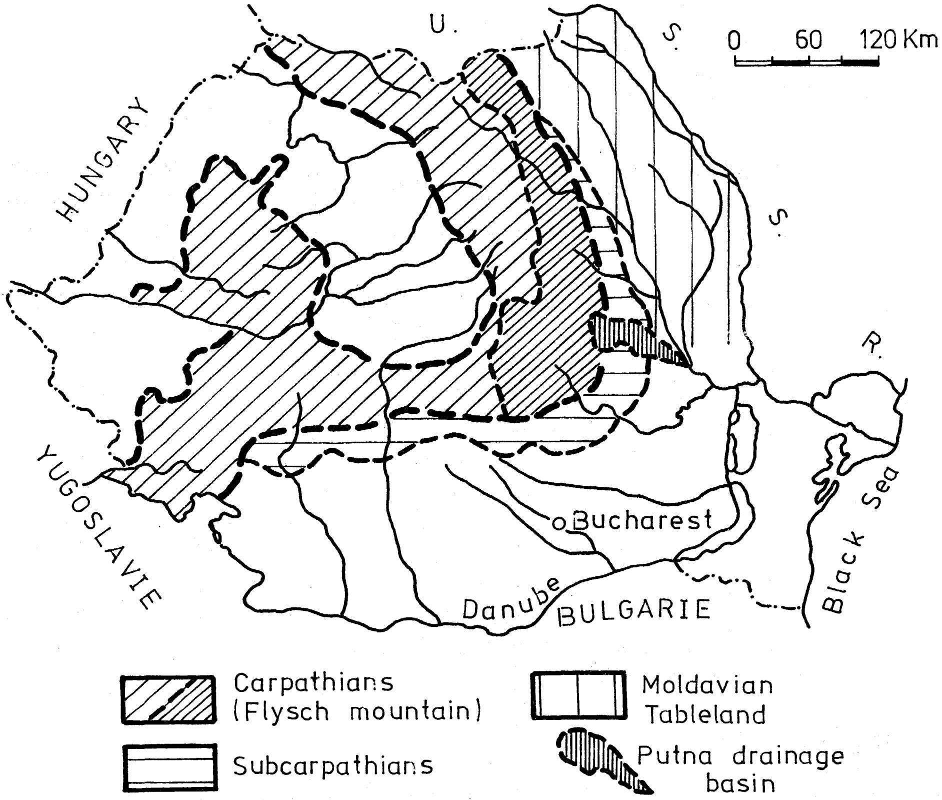


***Fig. 1** Location of the study areas within Romania.*

## MOLDAVIAN TABLELAND

This area, situated in the Eastern part of Romania, with an area of about 25 000 $km^2$, is characterized by soft sedimentary strata, with clays and marls alternating with sands, gently dipping in a southeastern direction (5–8%). The average annual precipitation is 450–600 mm and the greatest part of the land is used for agriculture or pastures. Severe or very severe erosion exists on about 50% of the land surface of the whole region, with most of the erosion resulting from heavy storms of over 20 mm.

Plot experiments undertaken for over 30 years (Popa, 1977; Baloiu & Giurma, 1979; Ionita & Ouatu, 1985) indicate that on the fields under cereals, the *effective erosion* varies between 225 t $km^{-2}$ $year^{-1}$ and 5550 t $km^{-2}$ $year^{-1}$, with a general average of about 2700 t $km^{-2}$ $year^{-1}$. If the gully sediment yields are also considered, the data obtained from over 20 years of field experiments indicate that this is on average about 3150 $km^{-2}$ $year^{-1}$

(Motoc *et al.*, 1979). On the Moldavian Tableland the average effective erosion is therefore at least 2250–3000 t km$^{-2}$ year$^{-1}$.

Date relating to measurements undertaken for periods of over 20 years indicate that from basins of order IV and greater, sediment yields vary between 14 and 694 t km$^{-2}$ year$^{-1}$. It is, however, important to note a special situation which strongly influences the sediment delivery ratio from the Moldavian Tableland. This relates to the presence of about 800 small reservoirs, some up to 400–600 years old, which retain some of the sediment transported by the rivers. The amount of sediment deposited in some of the reservoirs has been evaluated in order to take into account the trapping of sediment in the reservoirs. The measurement of sediment yield from the drainage basins have therefore been corrected in order to estimate the natural sediment delivery ratios which have been related to the Strahler order data. (Table 1, Fig. 2). These data demonstrate two important trends. Firstly, the sediment delivery ratios decrease very rapidly up to the level of the basins of order IV. This can be accounted for by the importance of local storms during much of the year. Only during the spring floods does sediment transport extend over all the drainage basins larger than those of order IV.

***Table 1*** *The variation of sediment delivery ratio (%) with channel network order in the three study areas*

| *Region* | *Channel network order (Strahler's system)* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *I* | *II* | *III* | *IV* | *V* | *VI* | *VII* |
| *Flysch Mountains* | *100.0* | *65.2* | *42.2* | *33.2* | *26.1* | *20.0* | - |
| *Subcarpathians* | - | *100.0* | *80.9* | *61.6* | *45.6* | *30.0* | *25.0* |
| *Moldavian Tableland* | *100.0* | *49.5* | *34.6* | *19.0* | *12.0* | *5.5* | *3.5* |

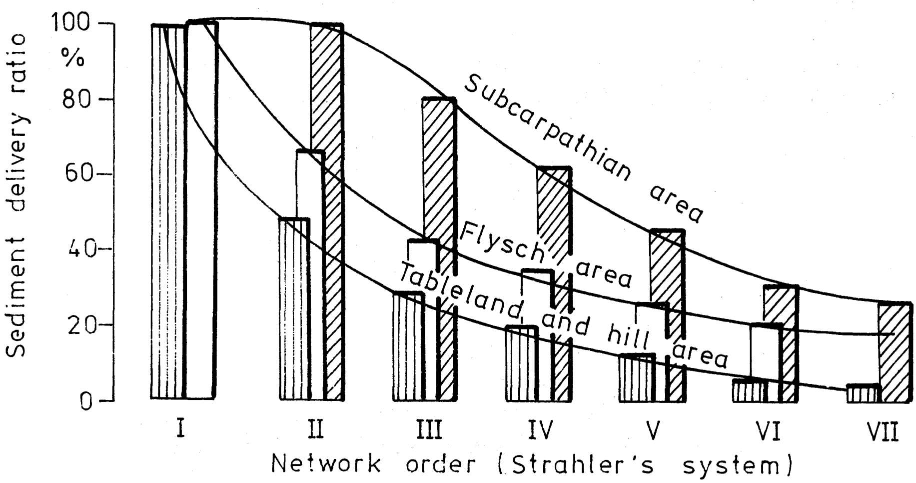


***Fig. 2*** *Sediment delivery ratio related to channel network order.*

Secondly, under the present morphoclimatic conditions of the Moldavian Tableland the very great difference between the effective erosion rate and the sediment yield of the drainage basins, is a reflection of the powerful colluviation processes and the active deposition of sediment at the base of the slopes.

## THE SUBCARPATHIANS

Within the territory of Romania, between the Carpathians and the extra-Carpathian hilly region, there is an area of geomorphological and geological transition, called the *Subcarpathians*. This is developed on neogene molasse deposits which have been folded and which show a marked tendency for mass movements (landslides, mud flows, earth flows etc). These phenomena considerably increase the slope erosion rate. Up to the basins of order III, any differentiation between the contributions from the slopes and from the headwater river channels to the sediment yield is very difficult. This is due to the fact that a large proportion of the mass movements (especially, landslides, earth flows, mud flows, creep, etc) are produced as a direct response to gully erosion. For this reason, the sediment yield of the IInd order basins has been considered to represent the *gross erosion*.

The Subcarpathians have an average altitude of 550 m and a maximum altitude in excess of 1000 m. The annual precipitation lies between 550 and 800 mm, with a high frequency of storms. The land is mainly used for grazing, forests and agriculture.

Sediment delivery ratios were evaluated for a sample of basins from the Putna River drainage basin in Vrancea. Measurements of sediment yield have been made for more than 20 years. The results show that the gross erosion frequently attains levels of 4000–5000 $m^3$ $km^{-2}$ $year^{-1}$ (Gaspar *et al.*, 1982). This is one of the highest erosion rates in the Carpathian region. Several prediction equations have been developed by Ichim & Radoane (1986), based on multivariate statistical analyses of the relationships between sediment yields and different controlling factors (28 independent variables, including the Strahler system of drainage basin ordering) for 63 small drainage basins. Among these, the best results were obtained for the equation:

$$\log Sy = 4.502 - 0.1782 \log \Omega + 0.7486 \log A^{a} + 0.0365 \log Cf + 0.1042 \log Dt + 0.3318 \log RR^{b} + 0.5439 \log Pmm^{d}$$

$$(R^2 \times 100 = 74\%)$$

where: *Sy* = sediment yield (t $year^{-1}$);
Ω = the drainage basin order;
*A* = drainage basin area ($km^2$);
*Cf* = form coefficient of the drainage basin;
*Dt* = the total density of the channel network (km $km^{-2}$);
*RR* = the relief ratio (m $km^{-1}$); and
*Pmm* = mean annual precipitation (mm).

Significance levels:

*a* = very high significance level (99.9%); *b* = high significance level (99.5%); *d* = low significance level (99%).

This equation was used to determine the sediment yield of small drainage basins in the Vrancea Subcarpathians and values close to those registered by field measurements were obtained.

To select the best function to represent the relationship between sediment yield and channel network order we tested 20 functions from which a computer program selected the optimum equation of the form:

$$Sy = \left[-17\ 918.84 + 25\ 062.81\ \Omega\ (-3563.21\Omega^2)\right] / \Omega^2$$

$$(n = 63;\ r = 0.557)$$

in which $Sy$ = sediment yield (t year$^{-1}$) and $\Omega$ = order of the drainage basin. Using this relationship we obtained for the drainage basins of order II ($A$ < 1 km$^2$) $Sy$ = 4538 t km$^{-2}$ year$^{-1}$. This was taken as an average value of gross erosion. It is comparable with the values obtained in some experimental basins by Gaspar *et al.* (1982) and by means of the equation proposed by Ichim & Radoane (1986). This value enabled us to calculate the sediment delivery ratios shown in Table 1 and Fig. 2. To check the results obtained for the different network orders we used the measured data for some river sections on the Putna river.

When compared with the Moldavian Tableland and the Flysch Mountains, the sediment delivery ratios in the Subcarpathians are the greatest. This can be accounted for by contrasts in the magnitude and frequency characteristics of the discharge regime (the flow volume in the Subcarpathians is generally greater than that in the Moldavian Tableland), by differences in the degree of erodibility of the rocks (greater in the Subcarpathians than in the Flysch Mountains) and by the increased incidence of landslides and mud flows and their role in the direct transfer of sediment into river channels.

## THE FLYSCH MOUNTAINS

In the Septentrional and Eastern Carpathians, the Flysch represents one of the most extensive lithological complexes. Within Romania's territory it extends to a maximum of almost 100 km. One of its major characteristics is the alternate layers of sandstone, marls, clay schist and sometimes conglomerates which are strongly folded.

The maximum altitude is 2508 m (Omul peak in the Bucegi Mountains), but except for this mountain, the area lies below 2000 m and has an average altitude of 300–500 m. Unlike the Subcarpathians, mass movement processes play a more limited role in the transfer of material from the slopes into the river channels. With a few exceptions, almost the whole mountain area is covered in mixed woodland. The mean annual precipitation lies between 600–1200 mm year$^{-1}$ with a monthly maximum in June, and a lack of severe storms. Under these conditions the effective erosion rates and the sediment yields are much smaller than in the Subcarpathians.

As in the case of the Subcarpathians, the sediment yields of small drainage basins (order I, Strahler's system) have been taken to represent the gross erosion.

Sediment yield was evaluated using an equation of the form:

$$\log Sy = 7.985 + 0.8138 \log A - 0.304 \log Rb + 0.1486 \log Dt - 0.1547 \log RR + 0.089 \log Af - 1.571 \log Pmm$$

$$(R^2 \times 100 = 92\%)$$

where *Rb* = bifurcation ratio; and *Af* = afforested coefficient (%) established by Ichim & Radoane (1986) for small drainage basins in the Flysch Mountains. To examine the relationship between sediment yield and the order of the drainage basin, the same procedure as used for the Subcarpathians area was followed. This produced the relationship:

$$Sy = \left[-4493.45 + 5826.65\,\Omega\,(-671.06\,\Omega^2)\right]/\Omega^2 \quad (n = 36;\ r = 0.606)$$

The gross erosion was estimated by this equation to lie between 1000–1500 t $km^{-2}$ $year^{-1}$, with an average of 1255 t $km^{-2}$ $year^{-1}$ for the basins of order I. A comparison of these data with the results of the experimental investigations of small drainage basins and experimental plots (Arghiriade *et al.,* 1960; Ichim *et al.,* 1979; Radoane, 1981; Gasper *et al.,* 1982) show that the results are reasonable. On this basis, the sediment yield of the Putna river basin (Vrancea) was determined for network orders up to order IV. Measurements from several river cross-sections were also available. The sediment delivery ratios listed in Table 1 and Fig. 2 were thereby calculated.

The sediment delivery ratios of the Flysch areas are greater than those of the Moldavian Tableland, but smaller than in the Subcarpathians. The increased incidence of more resistant rocks causes the material transferred from the slopes into the river channels to be coarser, and therefore the rates of transfer to be slower. The suspended sediment loads are therefore less than those transported by the Subcarpathians rivers where clays and marls, the more highly erodible rocks, dominate. This is despite the fact that the runoff is greater than in the Moldavian Tableland and Subcarpathians. It must also be noted that the mass movement processes, which can be important in the transfer of materials from the slopes into the river-channels, are not as significant as those in the Subcarpathians.

## CONCLUSIONS

The variation of the sediment delivery ratios in the three areas investigated falls within the limits of the general tendencies identified for other areas of the world. This is further indicated by the relationships between sediment yield and drainage basin shown in Fig. 3. The marked differences between the

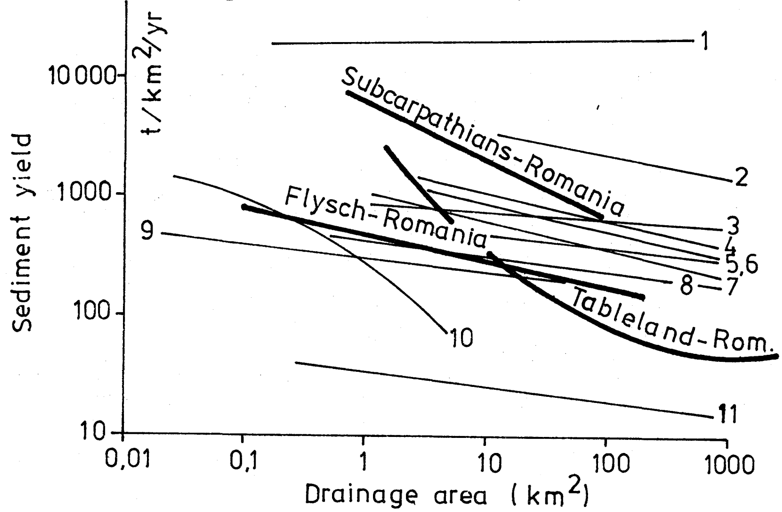


*Fig. 3 Relationships between sediment yield and drainage basin area for the three study areas superimposed on those portrayed by Walling (1983) for other areas of the world.*

three study areas can be attributed to contrasts in the magnitude and frequency of the discharge and in the degree of erodibility of the rock.

In situations where the rocks are easily eroded, but the discharge within the small basins is torrential in character, the sediment delivery ratio decreases markedly with an increase of the network order. This is because only during the spring flood period does the delivery system extend from the sediment sources to the outlet of the basins greater than order VII–VIII.

In the other situations more efficient delivery exists in small basins. In the Subcarpathian area, the relief, the greater amount of precipitation and the highly erodible rocks, provide a high sediment delivery ratio. In the Flysch Mountains, the volume of runoff is greater, and at the level of IVth order networks the water flow is more rapid, but the more resistant rocks are dominant and the gross erosion and the delivery ratio are both reduced. In the Moldavian hills the low contemporary delivery ratios indicate strong colluviation and glacis development at the base of the slopes.

**Acknowledgements** The author is grateful to Professor Des Walling from Exeter University, UK, for his helpful assistance.

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