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Relationships between suspended sediment load discharge and the total number and length of stream segments

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The discharge of suspended sediment load is an important indicator for estimating the intensity of erosional processes in drainage basins, but the laborious methodology required to establish it accounts for the small number of measurement stations. Therefore indirect evaluation methods, have been used, such as the number of stream segments and the sum of their lengths has been established by means of geometric progression individualizing drainage morphometrical models. In order to check if suspended sediment load is or not influenced by the sums of the number and lengths of stream segments the Bârlad basin has been taken as case study. Physico-geographical factors and the resistance of geological formations in this basin vary very little from one subbasin to another. The positive results obtained have enabled checking up these relationships in over 50 drainage basins of Romania located in the Carpathian Arc and in the Subcarpathian and Plateau areas. Because of great diversity of physico-geographical conditions within the analyzed basins lower determination coefficient values have been obtained.

Key words: Drainage model, number of segments, network length.

INTRODUCTION

The study of suspended sediment load discharge, a synthetic indicator of the intensity of erosional processes, is of great scientific and practical interest for its economic effects that should be taken into consideration in elaborating territorial planning schemes. The huge diversity of natural and anthropic conditions in the territory interacting, determine the spatial variation of erosion processes and the quantity of suspended sediment load. The effects of erosion on slopes and on the network of channels is wide-ranging, for example:

- Erosion on slopes, produces soil wash, decreases fertility and thus diminishes agricultural production.
- sediment load in channels causes floodplain alluviation, silts storage lakes and channels, blocks bottom discharge and water intakes, the formation of holms, also changing and deforming the channels, etc. The silting of reservoirs diminishes their useful water volume which may not be recovered given that removing sediments is not cost-effective.

The discharge of sediment load in Romania does not observe the general rule of vertical zoning as the majority of physico-geographical factors do. On the contrary, the smallest quantities of suspended sediment yield (below 0.5 t/ha. year) are found on the highest Carpathian summits and the plane area, highest quantities (over 25 t/ha. year) occurring in the curvature Subcarpathians. The sediment load regime is strongly connected to torrential precipitation, because more than 50% of the annual alluvia volume is discharged during high flood waters recorded less than 30 days per year (Diaconu, 1994). The contribution of the big relief units to the

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formation of the sediment load budget is distinctively different. Thus, the Subcarpathian area, which covers only 12% of the Romanian territory, yields 44% of the total volume of alluvia (Ichim et al., 1989).

Erosional processes in Romania affect approximately 7.3 million ha out of which over 5 million ha are severely impaired (Moțoc, 1982) and the trend is increasing because of massive and uncontrolled logging as forests have been returned to their former owners or heirs.

As a matter of scientific and practical interest, sediment discharge was studied both at institutional and individual level. At institutional level, systematic measurements and detailed studies have been made by the National Institute of Hydrology and Water Management (INHGA), network providing a substantial database for over 400 water-gauge stations. The first substantial paper devoted to the problem of sediment load discharge in Romania was due to Diaconu (1971) who synthesizes the conclusions of processing a very large volume of data. The spatial distribution of this phenomenon is reported also by Ujvary (1959), subsequently modified and completed by Diaconu and School of Pângaraţi headed by Professor Ichim and later by Maria Radoane who devoted much energy and time to studying suspended sediment yield. Noteworthy, this is the only research team in Romanian geography which has obtained remarkable results in this field. As interesting were the symposia on the "*Origin and Effluent of Sediment Yields*" and the multitude of works published on this topic. The effects of erosional processes and of the flow of suspended sediment load on the silting of storage lakes and on the management of water resources in Romania are presented in detail by Rădoane and Rădoane (2005) and Rădoane et al. (1999).

Special results were obtained by professor Moţoc (1982), with regard to the effluents of sediment yield in the big relief units of Romania in terms of the types of morphogenetic processes. The studies of representative basins carried out at Aldeni and Perieni stations have made a major contribution to the effect of erosional processes on agricultural terrains cultivated with different types of crops (Ioniţă et al., 1989).

In forestry, the team led by Gaspar (1979) obtained very good results by using the observations and measurements made for representative basins located in the forest area. The problem has been frequently discussed also in numerous contributions by specialists in hydraulics, hydrotechnics, etc.

Out of the multitude of environmental factors and complex relationships causing and influencing the discharge of sediment load, the present study focuses only on the contribution of the morphometrical model of drainage, the stock of sediment yield, yet without overlooking the part played by other environmental factors.

In order to find out the connections existing between the morphometrical characteristics of drainage basins and the discharge of sediment load as an indicator of the intensity of erosional processes, detailed researches on individualized regions or drainage basins were carried out. Thus, variations in the quantity sediment load in 22 representative basins of Spain with emphasis on the influence of climatic conditions, topography, land use, basin slope, the distance from watershed to discharge point, etc. were studied by Gert et al. (2003). Ferraresi (1990) looked into 20 representative basins located in the north of Italy, establishing correlations between the yearly volume of precipitation and total sediment yield. Out of the multitude of 30 factors involved in sediment yield, Ghadimi and Ghoddosi (1999) found 7 factors to be representative, (total length of channel network, the density of 2nd-order stream segments, etc.) which showed good correlation coefficients. Habibnejad et al. (2010) studied the factors influencing the discharge of sediment load in two basins situated in the north of Iran and established significant correlations between sediment load and the characteristics of the basins. Out of 104 variables, he found good correlations between sediment yield and land use, afforestation coefficient, and the yearly average liquid discharge.

There is a large scale use of GIS (Geographic Information Systems) methodologies to quantify the control factors of soils erosion universal equation. Such a trial covered two small basins in Romania (Patriche et al., 2006). Starting from the already existing models, the forecasts made on liquid discharges and suspended sediment load were analyzed with tested yields (Croke and Nethery, 2006).

METHODOLOGY

The purpose of this paper is to prove that the number and length of the network of stream segments should be taken into consideration when elaborating prognosis models of suspended sediment discharge. The current stream network morphometry is the result of all erosional processes that have been taking place on the contour level of drainage basins during their evolution, carrying encoded information regarding the relationships between form and agent that may be used both for scientific and practical purposes. In order to elaborate morphometrical models, for the drainage network, the Horton-Strahler classification system has been resorted to.

Researchers have been using Gravelius classification system which starts from big to small, from the mainstream basically from 1st-order streams up to the remotest highest-order arteries. In 1945, Horton reversed the order by assigning 1st-order to the smallest arteries instead of the main–stream, arteries that can be morphologically evidenced, and have the capacity to orientate and organize overland flow, and which do not receive any tributary along their course. The system was completed and finalized by Strahler (1952) who assumes that a 2nd-order stream results from the junction of two 1st-order streams, and a 3rd-order stream results from the junction of two 2nd-order streams up to the mainstream, which are the stream segments. This classification sets a number of rules that must be applied whenever proceeding to establishing a hierarchy. Thus a certain-order stream may receive lower-order tributaries without modifying its order of magnitude the latter changing, only if the respective stream joins another stream segment of the same order of magnitude.

Using this classification system, the database was obtained by digitizing, the drainage network from maps on the scale of 1:25 000 in Horton - Strahler classification system. In this way, the number of stream segments of increasingly successive orders and their lengths has been established. The database included a series of information regarding the network of river segments of various orders, such as hydronym and order and length. Next, the database was topologically checked, so that the line vector be without: intersections, overlapping, free segments, etc.

Digitization of the drainage network started from the 2nd-order stream segment upwards because starting with this order enables a better individualization of the start point revealed by the inflexion of the contour levels. In case of 1st-order stream segments this point cannot be identified with precision, so that the operator intervenes subjectively, hence the values assigned to 1st- order morphological elements in relation with the general trend of the progression can be either too low or too high. Taking into consideration that the law holds in most cases, 1st-order values can be easily assessed by calculations so that the work volume is reduced by half.

From the progression of the number of river segments and summed lengths of increasingly successive orders, the total values for drainage basins and subbasins can be established both for the Bârlad, case study and for all the basins in Romania studied so far.

Data on the multi-annual average discharges of suspended sediment, load (1982 to 2007) in representative basins smaller than 1 000 km^2, that have not any reservoirs were obtained by direct measurements of suspended sediment load. These data were supplied by the National Institute of Hydrology and Water Management.

RESULTS AND DISCUSSION

Drainage model of the Bârlad basin

The model was elaborated and tested both for the Bârlad basin, a lefthandside tributary of the Siret River and for several smaller basins in Romania controlled by water-gauge stations located in different physico-geographical conditions.

The Bârlad basin covers 7253 km^2, Its lithology consisting of sedimentary formations not very different in terms of resistance to erosion. From a geomorphological point of view, four major relief units shaped by the spatial variability of the physico-geographical factors can be distinguished: the Central Moldavian Plateau to the north, the Tutova Hills to the west, Fălciului Hills in the south-east and the Lower Siret Plain to the south) (Figure 1). The studied area extends at 0°58'53" East Longitude between Meridians 27°03'41'' and 28°01'34'' and at 1°25'42'' North Latitude between Parallels 45°40'15'' and 47°05'57''. Ela-borating and testing the drainage model implied establishing the number of stream segments and the sum of their lengths of increasingly successive orders both in the Bârlad basin, (order of magnitude 8), and in the 13 subbasins with water discharge and suspended sediment load registered by the water-gauge stations.

Summing up and analyzing the number of stream segments of increasingly successive orders has yielded a row of values corresponding to the orders of magnitude from two to eight. Their graphical presentation in semi-logarithmic coordinates, in term of the order magnitude, indicates that *the numbers of stream segments of successively higher orders in a given drainage basin tends to form a decreasing geometric progression in which the first term N_1 is the number of first-order streams and the ratio is the confluence ratio R_c* (Figure 2a) (Zăvoianu, 1985). The confluence ratio is calculated by the arithmetic mean, the weighted average by the number of stream segments of each order, or the method of chosen points (Figure 2a). In the present paper, the progression ratio has been established by the method of chosen points, that is the values obtained for the second and the fourth order by relation $Rc = \sqrt{N2/N4}$

In using this relation the idea was to highlight lower-order of magnitude in assessing the ratios of these progressions, because statistically these lower orders have the greatest share in terms of higher-order segments which being numerically few, may deviate more or less from the rule. The confluence ratio is used to calculate the values of 1st-order stream segments by proceeding from 2nd-order ones: similarly, the other values are calculated in order to compare the differences between the values obtained by direct determination and those yielded by calculation.

Starting from the properties of geometric progressions the total number of stream segments (ΣN) can be established by summing up the measured values, or by the formula:

$$\Sigma N = N_u (1-R_c^u) / (1-R_c)$$

where:

N_u - number of segments calculated for the main stream order of magnitude,
R_c – confluence ratio,
$_u$ – mainstream order of magnitude (Horton, 1945; Zăvoianu, 1985).

Summing up the lengths of digitized stream segments and classifiying them by increasingly successive orders of magnitude has yielded a row of data represented on the same diagram in order-dependent semi-logarithmic coordinates, the result being also a decreasing geometric progression. This shows that the sums of the lengths of stream segments of successively higher orders tend to form a decreasing geometric series in which the first term is the summed length L_1 of first-order streams and the ratio is the ratio R_L of successive summed lengths (Figure 2b) (Horton, 1945; Zăvoianu, 1985). For calculating the ratio of summed lengths, the same rule as in the case of the number of stream segments–is applied. Mentioning this law as a component part of the drainage model is indeed necessary, because the values established in term of orders and as sum are useful also for determining drainage density and implicitly the length of overland flow. The sum of the length of stream segments (ΣL) may be calculated either by directly summing up the lengths of order of magnitude or by using the following relation (Zăvoianu, 1985):

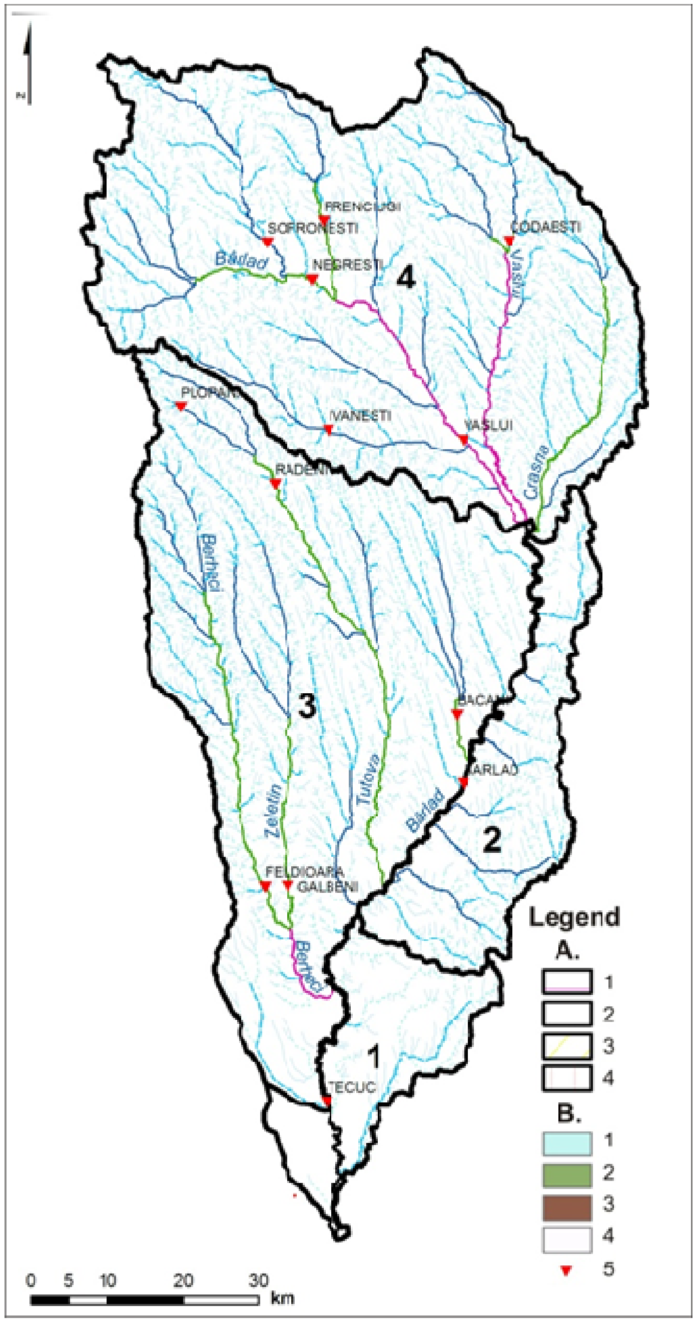

Figure 1. Map of relief units in the Bârlad basin hypsometric steps, water-gauge stations. **A**. Units of relief: **1,** Tecuci Plain, **2,** Fălciu Hills, **3,** Tutova Hills, **4,** Central Moldavian Plateau. **B**. Hypsometric steps: **1,** under 100 m, **2,** 100 m, 1 - 200 m, **3,** 200, 1 - 400 m, **4,** over 400.1 m. **5,** water-gauge stations.

$\Sigma L = L_u (1 - R_L^u) / (1 - R_L)$ where:

L_u – calculated length of the highest order segment;
R_L – ratio of lengths;
$_u$ – mainstream order of magnitude.

Referring the ratio of summated length to the number of stream segments, a third series of data, representing the average length of stream segments are obtained. The law thus established states that: *the average lengths of stream segments of successively higher orders in a basin tend to approximate an increasing geometric series in which the first term l_1 is the average length of first-order segments* (Figure 2c) Zăvoianu, 1985). The ratio r_l of

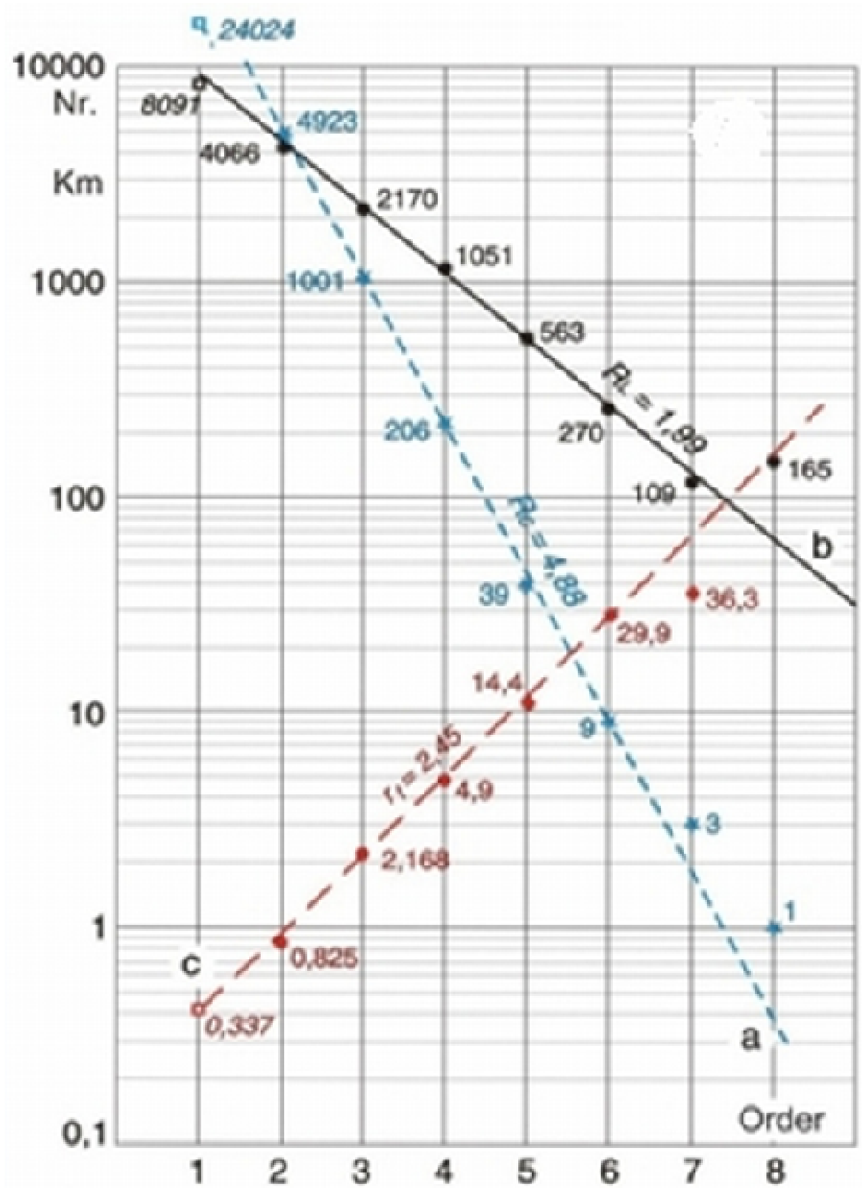

Figure 2. The morphometrical model of drainage in the Bârlad basin. **a,** law of regression of numbers of streams segments; **b**, law of regression of summed stream lengths; (in km); **c**, law of regression of average stream lengths (in km).

(successive average lengths can be established also by means of the quotient between the confluence ratio (R_c) and the summed lengths (R_L).

Having in view that the erosion processes start on slopes, continuing in the channel network, it follows that the degree of relief fragmentation and the length of the stream network may influence suspended sediment yield. Therefore, the study focussed on the basins, the substrate of which is found in unconsolidated rocks or on a basin area having little to the action of the sub-aerial agents, in which case suspended sediment yield is more abundant.

In order to verify this assumption, morphometrical models have been determined for all 13 subbasins of the Bârlad basin, for which data from direct measurements were available. The representation in normal coordinates of sediment load discharge in terms of summed number of stream segments, proves that a good direct relationship between the two elements does exist (determination coefficient of 0.983) (Figure 3). Because in normal coordinates there are differences between extreme values, the degree of value scatttering can be analyzed only by using logarithmic coordinates and the location of drainage basins within the geomorphological units. In this

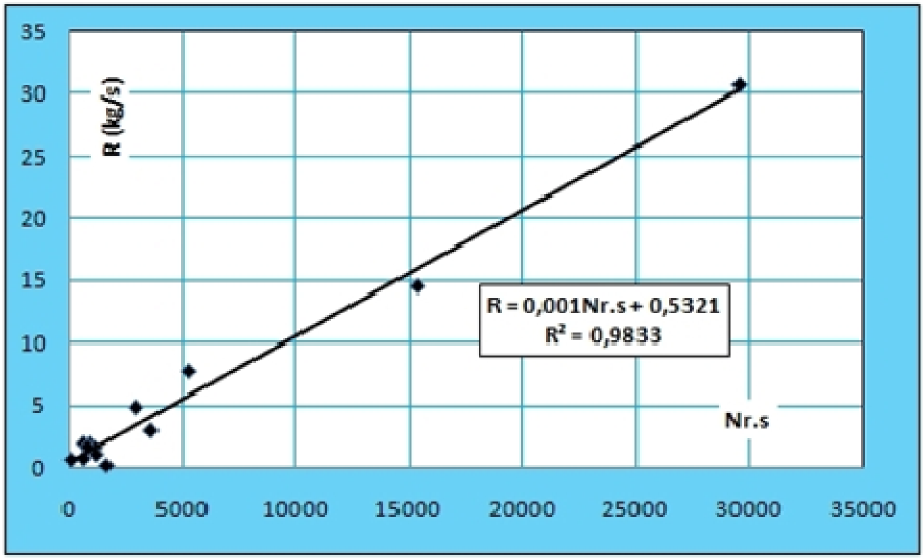

Figure 3. Relationship between suspended sediment load discharges and the total number of stream segments in the Bârlad basin in normal coordinates.

way two relations were singled out (Figure 3).

Thus, a first relation holds for the Central Moldavian Plateau and the rest of the basin outside the Tutovei Hills (determination coefficient of 0.979) and a second one for the Tutova Hills (lower determination coefficient 0.693) (Figure 4). Comparing the two relations, it appears that suspended sediment discharge for the same number of stream segments is higher in the Central Moldavian Plateau than in the Tutovei Hills.

The length of the hydrographical network is a very impotant element for suspended sediment discharge.

As known, in low waters the sediment load in the channel is reduced, whereas in high flood waters the quantity of sediment transported is increasd. All channel processes developing in various order streams plays an important role in the formation and transportation of suspended sediment load. The graphical representation of suspended sediment discharge in terms of the sum of the length of stream segments established for all sub-basins equipped with water-gauge stations, highlights, in normal coordinates, a good direct relationship proven by a 0.983 determination coefficient (Figure 5). In order to assess the degree of dependence between the two variables, the value of the solid discharge registered at Negreşti Station on the Bârlad River has been dismissed as inconclusive. Grouping the values at the bottom part of the diagram and the large-scale variation of extreme values raise the same difficulties in analysing the extent of scattering and in using the relationships in normal coordinates to determine the values of basins that have the stream segments rather small.

Representing the values in logarithmic coordinates and grouping them by geomorphological units, reveals that the Tutova Hills have a determination coefficient of 0.869 and the Central Moldavian Plateau 0.976. At the same time, for the same length of the drainage network, suspended sediment discharge is lower in the former case than in the latter. The distinct slopes of the two relations suggest higher differences between the two units with basin areas and lower ones with larger areas (Figure 6). The scattering degree and the good determination coefficients for the whole Bârlad basin and the geomorphological units is due to the fact that erosion resistance in the Bârlad basin is quasi-homogeneous. Small differences from one basin to another exist also between the geographical factors causing the drainage of suspended sediment load. Under these conditions, the relations obtained can be used for assessing suspended sediment discharge in terms of the number of stream segments and length, provided the values are compared also to those yielded by other dependence relations.

Representative basins

The existence of a good dependence relationship between suspended sediment load discharges, number and length of river segements in Horton-Srahler's clasification system in basins that are quasi-homogeneity in regard of geological resistance and geographical conditions, raises the question of whether this relationship holds also under different conditions. This hypotheses, has been checked in some 50 basins of Romania covering less than 1000 sq. km each, located in distinct physico-geographical conditions. Basins located in mountain area at various altitudes underlain by hard, consolidated rocks for which information on the suspended sediment load discharge is available from

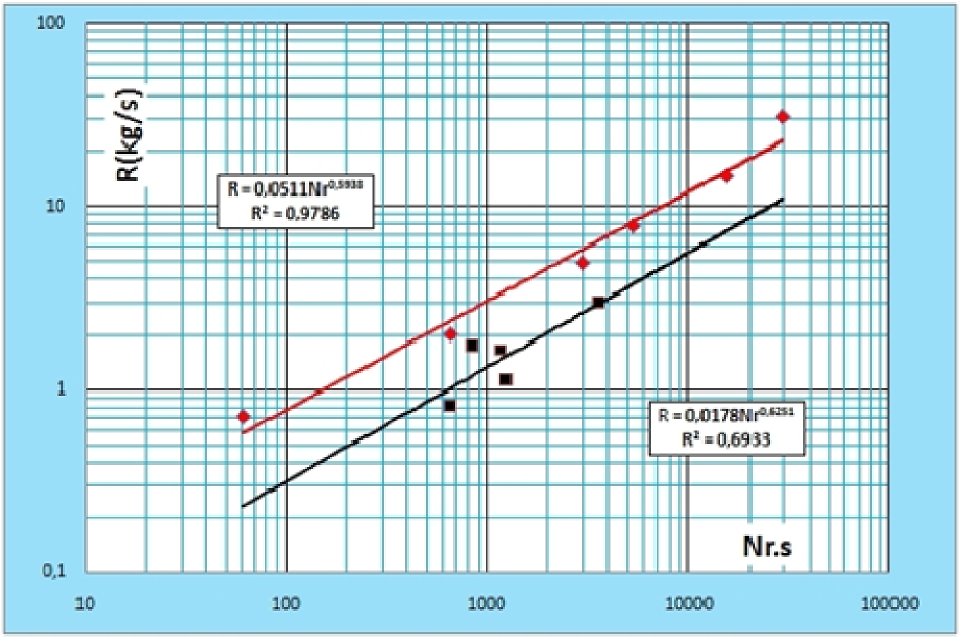

Figure 4. Relationship between suspended sediment load discharges and the total number of stream segments in the Bârlad basin in logarithmic coordinates.

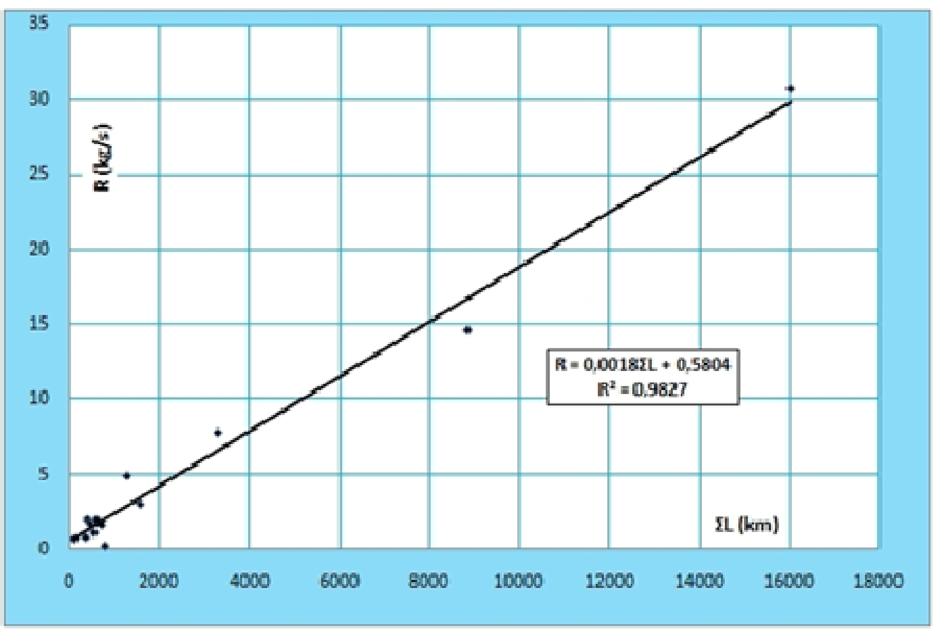

Figure 5. Relationship between suspended sediment load discharges and the total length of river segments in normal coordinates.

water-gauge stations; basins located in the Sub-carpathians and in plateau areas with a substrate of unconsolidated rocks little resistant to the action of sub-aerial agents. In each case, the number of stream segments and the sum of stream length by increasingly successive orders have been established, the sums by basins being controlled by water-gauge stations.

In order to check the dependence of suspended sediment load discharge on the number of stream segments, the two data rows have been analysed and

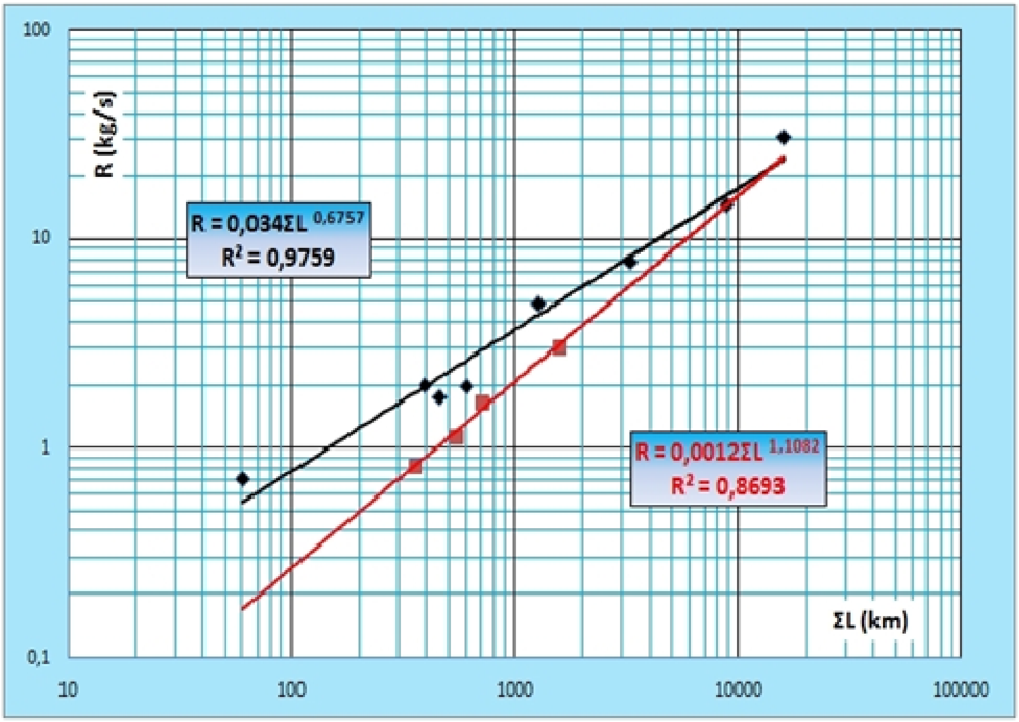

Figure 6. Relationship between suspended sediment load discharges and the total length of river segments in logarithmic coordinates.

the two variables correlated (Figure 7). In case of suspended sediment load discharges, values range between 0.030 and 0.1 kg/s with basins located in the mountain area underlain by consolidated rocks and between 10 and 30 kg/s with basins situated in the Subcarpathian region and the plateau area. The number of stream segments varied between 100 to 500 in the first case and 10 000 to 30 000 in the second case. The great difference between extreme values requires a graphical representation in logarithmical coordinates. The relation obtained indicates a direct dependence with the increase of sediment yield proportional to that in the number of stream segments. The later depends also on the increase of basin areas and the degree of relief fragmentation which are not dealt with in this paper. The determination coefficient obtained (0.711) is lower than in the case of the Bârlad basin, the scattering of values around the regression line proving that the number of stream segments does influence the formation of sediment load while the extent of value scattering provides evidences for the wide diversity of physico-geographical conditions within the drainage basins of Romania.

In order to test how the total length of stream segments, established according to the methodology, is or not involved in dimensioning of the sediment yield supply, the sum of the total-lengths for all the established morphometrical drainage models, elaborated has been used. The result was an array of values ranging from 60 km to over 10000 km. In this case, too, the values variation interval being is very large; it appeared that the analysis in normal coordinates was not the best approach, therefore logarithmic coordinates had to be resorted to; correlating suspended sediment load discharge with the sums of the total lengths in each basin indicates the fact that between the two elements there is a direct power-type relationship with a determination coefficient of 0.797 (Figure 8). As in the case of the relations between the suspended sediment load discharge and the number of stream segments, the higher value proves that the length of the stream network has a greater influence on the formation of suspended sediment discharge. Scattering, in its turn is justified by taking into consideration the great diversity of physico-geographical conditions of the analyzed hydrographic drainage basins studied, which the length of the stream network depend on. The determination coefficients obtained also prove that there are other variables that should be taken into consideration in order to obtain a functional dependence with a very good determination coefficient.

Conclusions

The efficient management of water resources within the context of sustainable development involves also the

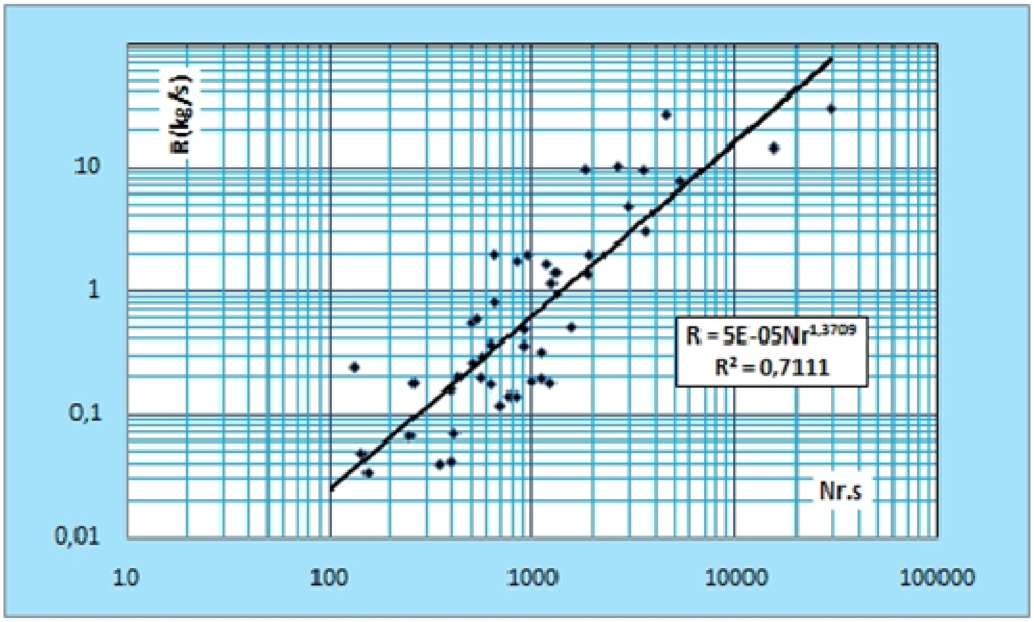

Figure 7. Relationship between suspended sediment load discharges and the total number of stream segments in representative basins of Romania.

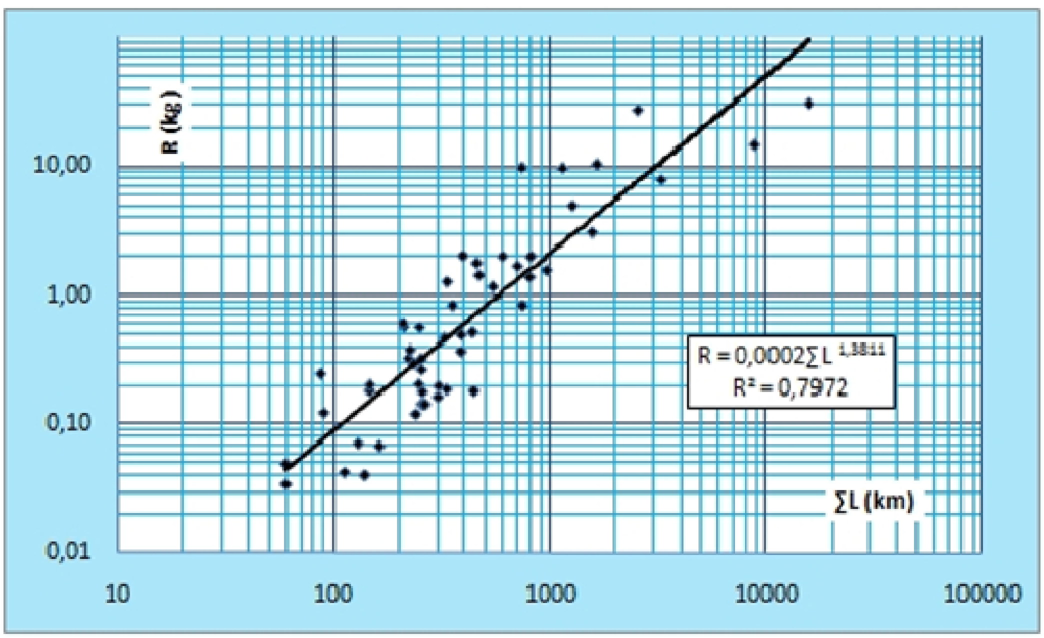

Figure 8. Relationship between suspended sediment load discharges and total length of river segments in representative basins of Romania.

quality of these resources and a knowledge of the suspended sediment load discharge, which has many economic implications. For example, the building and use of storage lakes to solve water shortage when water volumes are reduced requires information on the regime of suspended sediment discharge which influences directly the silting rate, that reduces drastically the useful water volume. There are many cases when a rapid silting rate caused by the transport of suspended sediment load, depleted the capacity of some reservoirs which became improper for the purpose they had been built for. In order that such constructions be efficient for over longer periods of time, it is important to know the quantities of suspended sediment load delivered by erosional processes, to the channel, further transported and discharged. The laborious methodology necessary to assess it and the small number of existing water-gauge stations, require finding indirect assessment methods by applying some relations generalized in the territory. The present study has made use of elements of drainage morphology, such as number and length of stream segments. The relationships between them and the suspended sediment discharge proved to be a very good one in our case-study and rather mediocre in the case of representative basins, as a result of the diversity of geographical factors related to erosional processes.

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