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DAN DUMITRIU (*)

SOURCE AREA LITHOLOGICAL CONTROL ON SEDIMENT DELIVERY RATIO IN TROTUŞ DRAINAGE BASIN (EASTERN CARPATHIANS)

ABSTRACT: DUMITRIU D., *Source area lithological control on sediment delivery ratio in Trotuş drainage basin (Eastern Carpathians).* (IT ISSN 0391-9838, 2014).

Depending on their response to erosion, we documented the occurrence of three distinct lithological groups within Trotuş drainage basin. The classification criteria were: the petrographic composition of geological formations, rock hardness, the relative relief and the longitudinal profile gradients for 2nd and 3rd order streams in the Strahler classification system. The two parameters employed in computing the sediment delivery ratio (i.e. the *gross erosion* and the *sediment yield*) were estimated for each lithological group based on the multiple regression equations introduced by Ichim & *alii* (1986). The aggregation of gross erosion estimates for each lithological group resulted in a total amount of approx. $107 x 10^5$ t of sediments eroded annually from the entire area of Trotuş drainage basin, of which $0.7 x 10^5$ tyr^{-1} were removed from the erosion resistant rocks area, $20.3 x 10^5$ tyr^{-1} from the area with moderate resistance to erosion, and $86 x 10^5$ tyr^{-1} from the area with low resistance to erosion. The sediment yield derived by using multiple regression was converted to the specific sediment yield, thus obtaining the following classes: 39-50 $tkm^{-2}yr^{-1}$ for high resistance areas; 220-350 $tkm^{-2}yr^{-1}$ for moderate resistance areas, and 800-1,900 $tkm^{-2}yr^{-1}$ for areas with low resistance to erosion. The values of the sediment delivery ratio reveal the increasingly larger sediment storage as we approach the junction with Siret river. Thus, in Lunca de Sus gauging station (located 14 km from the headwater) the delivery ratio is as high as 40%, as compared to 23% in Goioasa (54 km from the headwater), 15% in Târgu Ocna (90 km from the headwater), and just 7.6% of the total amount of eroded sediment evacuated annually in the drainage basin outlet.

KEY WORDS: Lithological control, Sediment delivery ratio, Stream order, Multiple regression equations, Eastern Carpathians.

REZUMAT: DUMITRIU D., *Influenţa litologiei ariilor sursă asupra raportului de efluenţă al aluviunilor din bazinul râului Trotuş (Carpaţii Orientali).*

În funcţie de comportamentul la eroziune, în cadrul bazinului hidrografic al râului Trotuş, au fost separate trei grupe litologice. Criteriile de separare au fost: compoziţia petrografică a formaţiunilor geologice, duritatea rocilor, energia de relief şi gradientul profilelor longitudinale al râurilor de ordinul 2 sau 3 în sistem Strahler. Cei doi parametri implicaţi în calculul raportului de efluenţă al aluviunilor (eroziunea efectivă sau totală şi producţia de aluviuni sau evacuată din bazin) au fost estimaţi pentru fiecare grupă litologică în parte cu ajutorul ecuaţiilor de regresie multiplă elaborate de către Ichim & *alii* (1986. Prin cumularea valorilor estimative ale eroziunii efective obţinute pentru fiecare grupă litologică, a rezultat faptul că de pe întreaga suprafaţă a bazinului râului Trotuş pot fi erodate într-un an aproximativ $107 x 10^5$ din care $0.7 x 10^5$ tyr^{-1} pentru arealul cu roci rezistente la eroziune, $20.3 x 10^5$ tyr^{-1} t pentru arealul cu rezistenţă moderată la eroziune şi $86 x 10^5$ tyr^{-1} pentru arealul cu rezistenţă slabă la eroziune. Valorile raportului de efluenţă pun în evidenţă stocajul din ce în ce mai mare al sedimentelor, pe măsură ce ne apropiem de confluenţa cu Siretul. Astfel, la staţia hidrometrică Lunca de Sus (situată la 14 km faţă de izvor) raportul de efluenţă este de 40%, la Goioasa (la 54 km faţă de izvor) de 23%, la Târgu Ocna (la 90 km faţă de izvor) de 15%, iar la ieşirea din bazin sunt evacuate doar 7.6% din totalul materialelor erodate într-un an.

CUVINTE CHEIE: Control litologic, Raport de efluenţă, Ordinul reţelei hidrografice, Ecuaţii de regresie, Carpaţii Orientali.

INTRODUCTION

Sediment production/delivery is considered one of the most important characteristics of a drainage basin (Verstraeten, 2006; de Vente & *alii*, 2007, 2011). This process has a major influence on riverbed morphology (Prosser & *alii*, 2001), on sediment deposition rates in reservoirs (Rădoane & Rădoane, 2005; Vanmaercke & *alii*, 2011) and, last but not least, on water quality, in general. The use of the term *sediment delivery* can be traced back at least as far as the work of Maner & Barnes (1953) and Glymph (1954) (Parsons & *alii*, 2006). Later on, the terms *Sediment Delivery Ratio* (*SDR*) defined as the ratio between the *sediment yield* (S_y, $tkm^{-2}year^{-1}$, estimated in a certain river section) and *gross erosion* (E, $tkm^{-2}year^{-1}$, from the drainage basin upstream the section), during a given time

(*) *Al. I. Cuza University of Iaşi, Faculty of Geography and Geology 22, Carol I Boulevard, Iaşi RO - 700505* - dndumitriu@yahoo.com

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interval (Roehl, 1962; Walling, 1983), was introduced and developed. Therefore, the *sediment delivery ratio* (SDR%) can be calculated using the equation:

$$\mathrm{SDR} = \frac{Sy}{E} x100 \qquad (1)$$

where S_y is average annual sediment yield per unit area and E is average annual erosion over that same area. In essence, SDR is a scaling factor used to accommodate differences in areal averaged sediment yields between measurement scales. It accounts for the amount of sediment that is actually transported from the eroding sources to the catchment outlet compared to the amount of soil that is detached over the same area above (Hua Lu & *alii*, 2006). The SDR value is closely related to several factors, such as: the nature of sediment sources, their position relative to the riverbed, the hillslope gradients and channel-bed slope, land use/land cover and rainfall-runoff factors (Klaghofer & *alii*, 1992; Molina & *alii*, 2008). SDR estimation methods can generally be grouped into three categories.

The first range of methods is based on data obtained by direct measurements on the sediment yield, the water discharge and water speed (Gregory & Walling, 1973). Unfortunately, these estimates can only be applied in small-sized catchments, since such detailed measurements cannot be extended to larger scale basins.

The second, and most commonly employed category of methods to date, is based on empirical regression equations which relate SDR to the most important morphological characteristics of drainage basins, such as the catchment area (Roehl, 1962; Walling, 1983; Wasson, 1994; Avendaño & *alii*, 1997; Onyando & *alii*, 2005; Boomer & *alii*, 2008). In this case, the most widely used is the *SDR-catchment area power function*:

$$\mathrm{SDR} = \alpha \mathrm{A} \beta \qquad (2)$$

where A is the catchment area (km^2), α and β are empirical parameters. This category also includes several models (among which the ones employed by us) taking into account not only the catchment area, but also a combination of drainage basin factors (Flaxman, 1972; Onstad, 1984; Ichim & Rădoane, 1987; Rădoane & Ichim, 1987; Neil & Mazari, 1993; Verstraeten & Poesen, 2001; Restrepo & *alii*, 2006; Grauso & *alii*, 2008; de Vente & *alii*, 2011). These models have emerged as a result of research showing that the sediment yield is in fact related not only to the catchment area, but also to the topography, climate, geology, soil, vegetation and land use/landcover, which in turn influence hydrologic processess.

Third category comprises of process-based physical models. Most of these estimate the sediment yield and deposition based on runoff data, erosion and deposition processess, river transport capacity and sediment residence time (de Roo & *alii*, 1989 - LISEM; Flanagan & Nearing, 1995 - WEPP; Morgan & *alii*, 1998 - EUROSEM; Schoorl & Veldkamp, 2001 - LAPSUS; Kirkby & *alii*, 2004 - PESERA) (Van Rompaey & *alii*, 2001, 2005, Verstraeten, 2006; Verstraeten & Prosser, 2008, Lu & Richard, 2008; de Vente & *alii*, 2011).

STUDY AREA

Trotuş drainage basin is located in the central-eastern sectors of the Eastern Carpathians and the Moldova Subcarpathians, and extends over 4,350 sq km (1/10 of Siret basin area) (fig. 1). According to Strahler's classification, Trotuş river basin is ranked as 8th order (Strahler, 1952, 1980). The basin overlies four distinct structural and lithological units, i.e., the marginal syncline, the Carpathian flysch, the peri-Carpathian molasse and the foredeep (s.str.) zone (fig. 2). 57,5% of the basin area (i.e., the upper and middle sectors) is occupied by rock outcrops pertaining to the Carpathian flysch (sandstone, conglomerate, marl and clay). The East-Carpathian flysch consists of five nappes extending eastward as follows: Ceahlău, Teleajen, Audia, Tarcău and Vrancei; the peri-Carpathian molasse domanin accounts for 23% of the basin area, i.e. the middle to lower basin transition zone (marl, clay, sand); 17,5% of the basin area consists of Quaternary deposits which prevail in the lower basin (gravel, sand, loess deposits); 1,7% of the basin pertains to the crystalline-Mesozoic area, located in the upper course, and comprising of crystalline schists, intrusive rocks and limestone. The slope gradients ranging from 15° to 30° are largely prevalent in this area, whereas slope gradients above 30° are rather infrequent. In the eastern part of the mountain area gradients ranging from 5° to 15° are the most common, while the lowlands are dominated by slope gradients below 5°. The thermal regime features annual average temperatures ranging from 3 to 7°C in the mountain area, 7 to 8.5°C in Dărmăneşti Depression and 8.5 to 9.5°C in the Subcarpathian area. The average annual precipitation ranges from 722 mmyr^{-1} in Trotuş Valley to nearly 1,000 mmyr^{-1} in the higher mountain area. These value drop by approx. 100 mmyr^{-1} in the central part of Dărmăneşti Depression and towards the Subcarpathian limit. The average annual discharge on Trotuş river recorded in Vrânceni gauging station is 35 m^{3}s^{-1}, whereas the maximum recorded value was 3,720 m^{3}s^{-1}, on July 29, 1991.

In the upper and middle sections of Trotus basin the forests cover nearly 61% of the area, the agricultural land accounts for 34% (of which 95% pastures and meadows, and 5% arable land), and the remaining 5% is allotted to other uses (i.e., buildings, roads, degraded land etc.). In the lower basin forests cover 31% of the total area, agricultural land, 49% (of which 15% arable land), whereas the remaining 20% corresponds to river channels, unproductive areas within the floodplains, built-up areas and highly degraded hillslopes (Dumitriu, 2007). The total length of Trotuş river is approx. 160 km. Over nearly 130 km from the headwater, the river comprises of a well-delineated single-thread channel, with a 1,5 average sinuosity index. In the lower course, i.e. the last 30 km, the channel

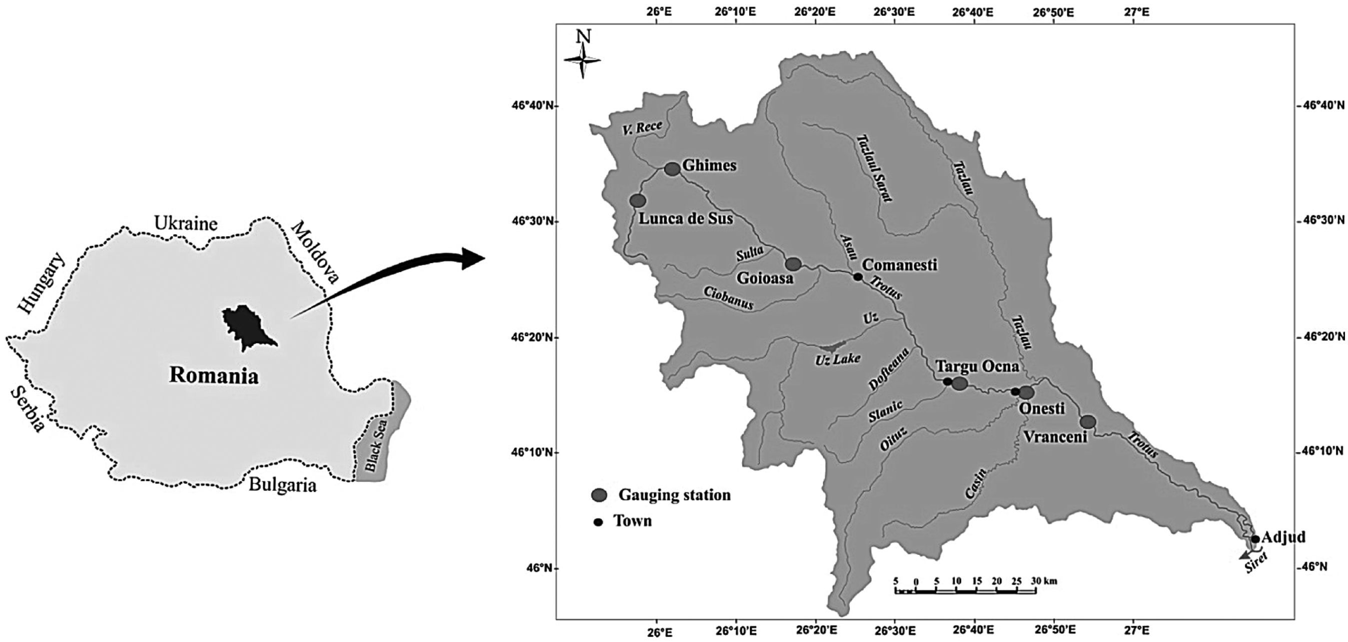


FIG. 1 - Study area location.

becomes braided. The average median diameter (D_{50}) of channel bed sediments over the entire 160 km is 71,3 mm, whereas the extreme values amount to 130 mm (Asău) and 20 mm (Adjud), respectively (Dumitriu, 2007; Dumitriu & *alii*, 2011). The slope gradient of the channel ranges from 0.17 mm^{-1} in the upper course (Lunca de Sus) to 0.018 mm^{-1} in the lower course (Adjud).

MATERIALS AND METHODS

Lithological entities zoning according to erosion resistance

In the early stage of the research we built the database comprising of data on the area and lithological composition of each geological formation. The required data were extracted from geological maps (scales 1:200,000 and 1:50,000) and lithological logs (Dinu, 1985; Grasu & *alii*, 1988, 1995, 1996, 1999, 2004); namely the areas belonging to each lithological entity were estimated based on the geological maps and the petrographic composition of each formation was extracted from the lithological logs. The second stage consisted in grouping petrographic entities from each geological formation according to their hardness. In order to perform this operation, the classifications introduced by Selby (1982); Ichim & *alii* (1984, 1998); Augustinus (1991), Attall & Lavé (2009) were used. These data were related to the ones obtained by measurements of the relative relief and gradients of the 3^{rd} order Strahler rivers longitudinal profiles. The two parameters (relative relief and longitudinal profiles gradient) were computed for a number of 1,959 3^{rd} order rivers. By using the above mentioned criteria, considering the specific conditions of Trotuş river basin, three distinct lithological groups with different resistance to erosion were separated.

Methods for Sediment Delivery Ratio (SDR) determination

Determining the values of gross erosion and sediment yield is based primarily on direct measurements performed in the field; however, when these data are scarce or lacking, indirect assessment methods are employed instead (Walling, 1983; Rădoane & Ichim, 1987; Reid & Dunne, 1996). Since gauging stations are unevenly distributed throughout Trotuş basin, a large portion of the study area remains ungauged (of the 20 gauging stations operating in the basin, 6 are located on river Trotuş and the others on its main tributaries). Consequently, the direct data were insufficient, thus prompting us to resort to an indirect assessment method, i.e., the multiple regression equations introduced by Ichim & *alii* (1986) for determining the sediment delivery ratio in relation to the drainage network order. The results thus obtained were compared to the data provided by Ichim & *alii* (1998) regarding the suspended sediment evacuation rates in 100 drainage basins less than 400 sq km in area (of which 40 located in the flysch area and 60 pertaining to the molasse domain). Gross erosion and sediment yield for each drainage basin greater or equal to 3^{rd} order for 2,471 basins (1,959 of 3^{rd} order, 401 of 4^{th} order, 95 of 5^{th} order, 15 of 6^{th} order and 3 of 7^{th} order) were computed. Ichim & Rădoane (1987) suggest that the gross erosion can be regarded as equal to the sediment yield in 1^{st} order catchments located in the flysch area, and 2^{nd} order catchments from the molasse area, respectively. These catchments do not exceed 1 sq km in area.

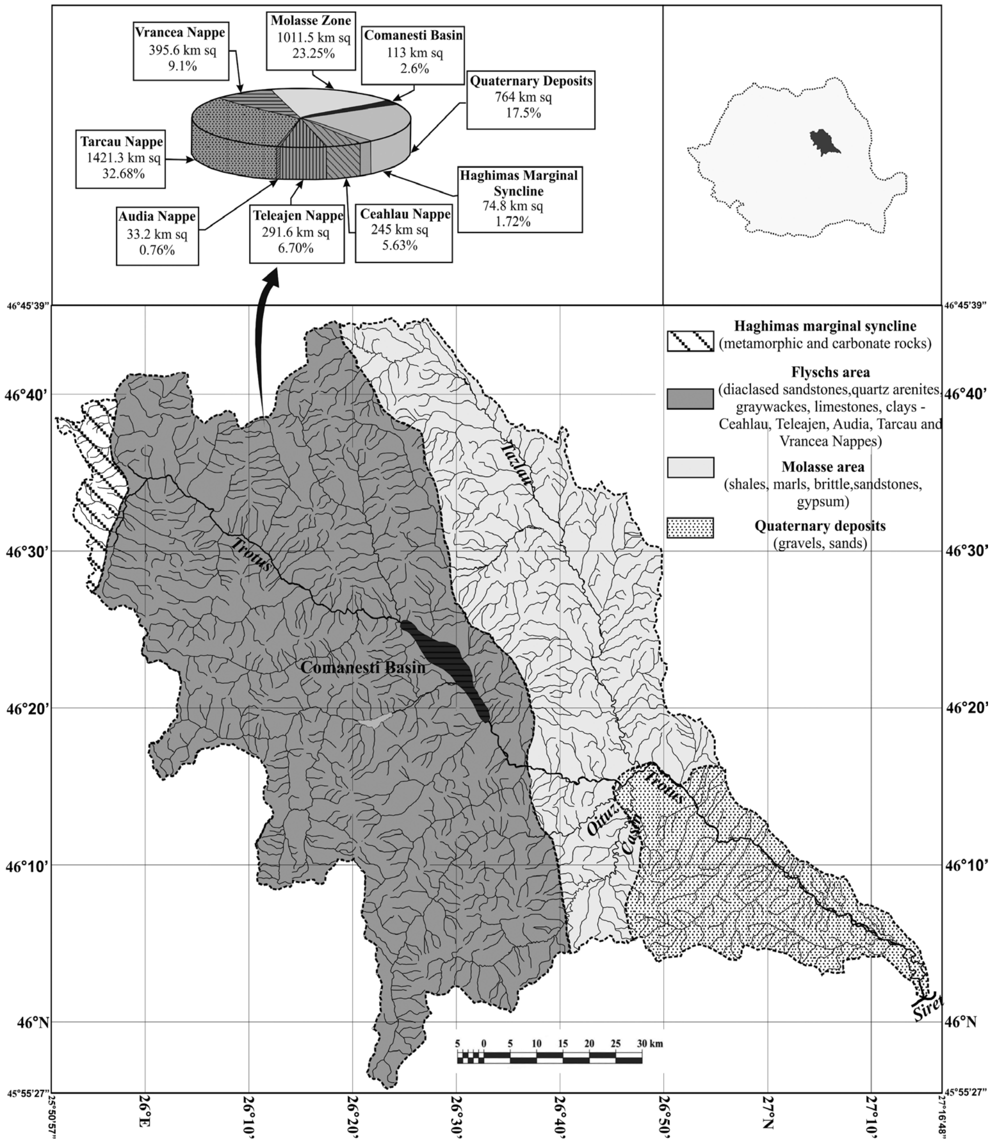


FIG. 2 - Bedrock geology of Trotus drainage basin and percentage of the main geological formations.

Upland gross erosion assessment

Hillslope gross erosion is regarded as the sum of sheet erosion, rill erosion, gully erosion and channel erosion in small catchments (Onstad, 1984). In the case of Trotuş basin, the equations of gross erosion developed by Ichim & *alii* (1986) were applied separately to the three types of areas classified in terms of the resistance to erosion. The equations used for estimating gross erosion in certain areas, by taking into account the rock resistance to erosion, are as follows:

(i) For areas with moderate resistance to erosion:

$$E = [-4493.45 + 5825.65\,\Omega\,(-671.06\,\Omega^2)]\,/\,\Omega^2 \qquad (3)$$

(n = 36; r = 0.606)

where *Ω* - is the drainage basin order.

(ii) For areas with low resistance to erosion:

$$E = [-17918.84 + 25062.81\,\Omega\,(-3563.21\,\Omega^2)]\,/\,\Omega^2, \qquad (4)$$

(n = 63; r = 0.557)

(iii) Since a function was not available for areas with high resistance to erosion, the following formula was used:

$$S_y = 72.443\ A^{-0.100} \qquad (5)$$

Sediment yield assessment by using river network magnitude order

The second parameter required for computing the sediment delivery ratio is the sediment yield at the exit from catchment area. For determining this parameter we took into account the basin zoning according to the resistance to erosion of lithological entities (Ichim & *alii*, 1986). The following equations were used:

(i) For areas with moderate resistance to erosion:

$$S_y = 7.985 + 0.8138 \log A - 0.304 \log F_f + 0.1486 \log D_d - 0.1547 \log R_r + 0.089 \log RR - 1.571 \log P_{mm} \quad (6)$$

where F_f - form factor; D_d - drainage network density ($kmkm^{-2}$); R_r - relief ratio (mkm^{-1}); P_{mm} - monthly average precipitation (mm).

(ii) For areas with low resistance to erosion:

$$\log S_y = 4.5402 - 0.1782 \log W + 0.7458 \log A + 0.0365 \log C_s - 0.1042 \log D_d + 0.3318 \log R_r - 0.5439 \log P_{mm} \quad (7)$$

(iii) For areas with high resistance to erosion a similar equation was not available, and thus the following one was used, in relation tothe catchment area:

$$S_y = 1{,}692\ A \quad (8)$$

These equations were developed solely for drainage basins below 6th order.

RESULTS AND DISCUSSION

Lithological groups according to their resistance to erosion

Based on the data regarding rock hardness, relative relief and longitudinal profiles gradients, we ranked three lithological groups displaying different levels of resistance to erosion, namely: *(i) a lithological group with high resistance to erosion; (ii) a lithological group with moderate resistance to erosion; (iii) a lithological group with low resistance to erosion* (table 1).

(i) the *lithological group with high resistance to erosion* extends over 1683.4 km^2 (i.e., 38.7% of the entire basin area), overlying the western and central sectors of the Carpathian flysch, accounting for the largest shares in terms of area in the upper basins of Oituz, Slănic, Dofteana, Uz, Ciobănuş and Asău (fig. 2);

TABLE 1 - Lithological groups according to their resistance to erosion

Lithological groups according to their resistance to erosion	Surface [km^2]	Surface % of drainage area	Relative hardness indices to erosion*
Lithological group with high resistance to erosion	1683,5	38,7	1,62
Lithological group with moderate resistance to erosion	938	21,6	1,41
Lithological group with low resistance to erosion	1728,5	39,7	1

* Relative hardness indices to erosion was computed using relief energy and longitudinal profiles gradient for rivers of 2nd and 3rd Strahler order. It was assigned the value of 1 for rock areas in which was computed the smallest values of the above parameters.

(ii) the *lithological group with moderate resistance to erosion* accounts for 21.6% of the drainage basin area and is characteristic for Trotuş upper basin, upstream of the junction with Sulţa river;

(iii) the *lithological group with low resistance to erosion* prevails in terms of extension (i.e., nearly 40% of the basin area), and occupies the entire area overlying Quaternary deposits and most of the molasse domain, with the exception of several small-sized patches with Burdigalian outcrops.

The relative resistance indices we derived are only valid, in general, in basins overlying rocks with relatively uniform behavior to erosion. In most cases, the relative resistance to erosion of certain types of rocks is strongly influenced by the age of the deposits, their thickness and tectonics. The situation encountered in Trotuş basin supports this assertion. Thus, the maximum values for elevation, relative relief and longitudinal profile gradients occur in basins such as Camenca, Asău and Uz, whereby Paleocene-Eocene limestone (Tarcău limestone) crops out, rather than in Hăghimaş marginal syncline, part of the of the East-Carpathian Crystalline-Mesozoic Zone, where crystalline schist, granodiorite, gneisse, crystalline limestone and limestone outcrops are prevalent, all of which are seemingly more resistant to erosion. If the actual hardness of rocks from the two areas were the only factor weighing in, the situation would be inverted, i.e., higher elevation and relative relief in Hăghimaş marginal syncline; however, the different time lapses while they were elevated and subjected to the action of external factors have weighed in significantly. Nevertheless, there are situations where the age criterion is no longer valid. For instance, Kliwa sandstones are regarded as more resistant than the Tarcău type, and yet in most basins from the East-Carpathian flysch, considering the relief energy and the longitudinal profile gradient criteria, the areas where the former type of sandstone (Kliwa) crops out rank in a lower resistance class. In this case, the difference lies in the thickness and massiveness of sandstone packs, which highly favour the latter type. In this context, Yatsu (1966) believes that the hardness of the same types of rocks varies depending on the intensity and time spent under the action of exogenous processes. Therefore, the overlying superficial deposits will display different properties depending on the rhythmic disposition of elemental lithological entities, the intensity of fissure formation, the degree of permeability and rock hardness. Reflecting on how superficial deposits mirror some properties of the substrate, Surdeanu (1984) stated that it is extremely difficult to accurately determine all the inherited traits. The author asserts that the cyclic dynamic evolution itself has resulted in similar physical and mechanical properties in the present stage in deposits developed based on different lithological substrates.

The gross erosion

By applying the set of equations on the three types of lithological classes occurring in Trotuş drainage basin the following values of gross erosion were obtained: (*i*) 72

$tkm^{-2}yr^{-1}$ for the area with high resistance to erosion; (*ii*) 1255 $tkm^{-2}yr^{-1}$ for the area with moderate resistance to erosion; and (*iii*) 5180 $tkm^{-2}yr^{-1}$ for the area with low resistance to erosion. By summing up the gross erosion values derived for each of the three lithological groups we determined that the amount of sediments removed annually from the entire Trotuş basin can be as high as 107x10^5 t, of which 0.7x10^5 tyr^{-1} were displaced from the area with high resistance to erosion, 20.3x10^5 tyr^{-1} from the area with moderate resistance, and 86x10^5 tyr^{-1} from the area with low resistance to erosion. Based on this data, we can conclude that about 80% of the overall gross erosion is generated by the area with low resistance to erosion, which accounts for just about 40% of Trotuş drainage basin area.

The sediment yield

By applying the regression equations we obtained values that were further converted to the sediment specific yield (SSY), resulting in the following spectrum for the sediment yield: (*i*) 39-50 $tkm^{-2}yr^{-1}$ in the area with high resistance to erosion; (*ii*) 220-350 $tkm^{-2}yr^{-1}$ in the area with moderate resistance to erosion and (*iii*) 800-1,900 $tkm^{-2}yr^{-1}$ in the area with low resistance to erosion.

For validation purposes, these values were compared to measurement data from gauging stations, and we concluded they can be considered adequate, if we take into account that only the suspended solid load is gauged in these stations (and not the bed load, as well), and the gauging period is lengthy enough (60 years), so that errors are acceptable (Vanmaercke & *alii*, 2012) (fig. 3 and table 2).

It can be noted that sediment yield values reflect accurately the lithological composition. As expected, higher rates for the sediments yield were recorded in areas with

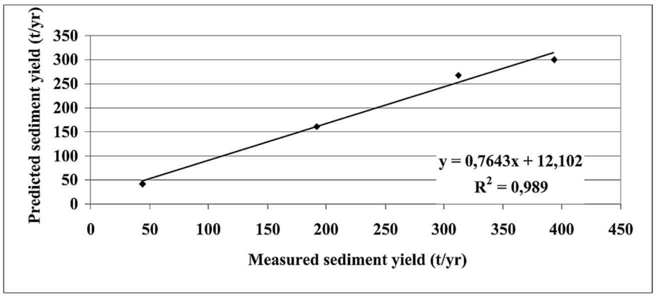


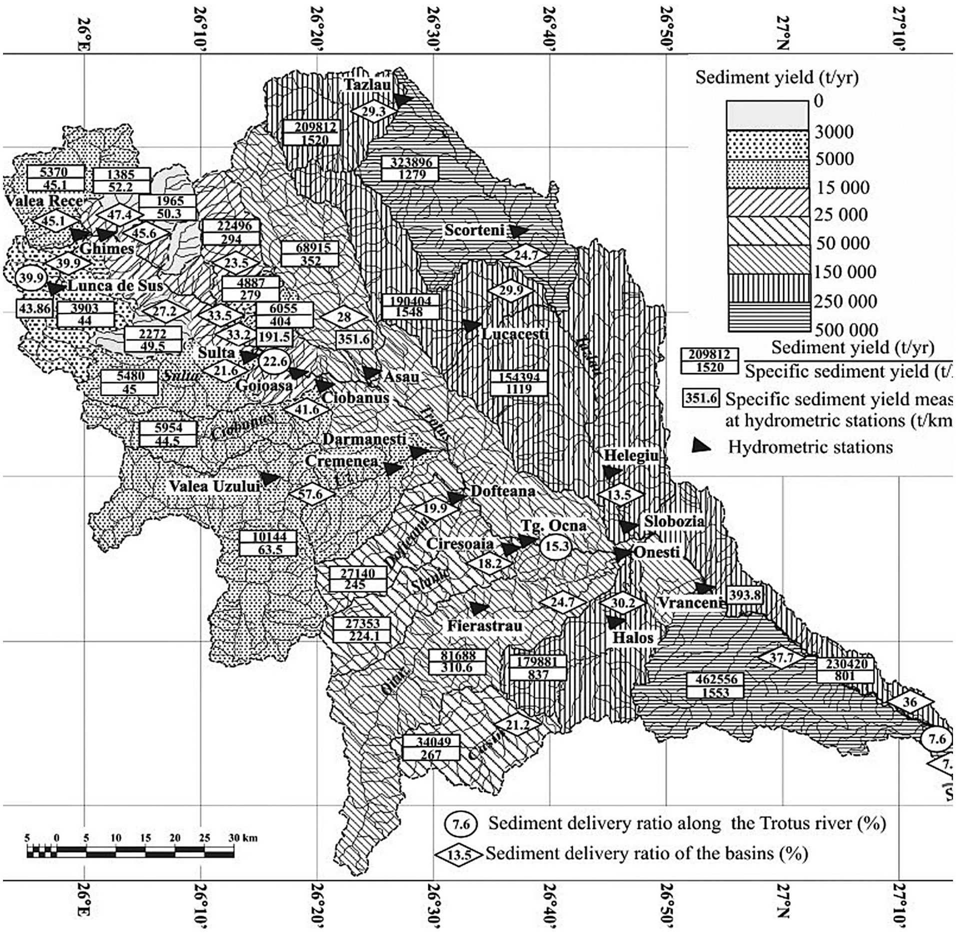
FIG 3 - Regression comparison between observed and predicted annual sediment yield.

TABLE 2 - Measured (1950-2010) and predicted sediment yield

Gauging stations	Basin area (km^2)	Discharge (m^3/s^{-1})	Specific sediment yield observed ($t/km^2/yr^{-1}$)	Specific sediment yield predicted ($t/km^2/yr^{-1}$)
Lunca de Sus	31.2	0.78	43.86	41.02
Goioasa	913.6	6.37	191.5	159.92
Targu Ocna	1893.31	17.08	283.5	266.88
Vranceni	4005.4	34.7	393	300.09

low resistance to erosion (molasse and avantfosse area), which coincide with the regions where the anthropogenic intervention on hillslopes has been strongest. Therefore, a sediment yields of over 300,000 tyr^{-1} was estimated for Tazlău middle basin, between Tazlău and Scorţeni, and on right side of Trotuş river, downstream of the confluence with Caşin river (fig. 4). In these sectors the estimated values were 323,826 tons (i.e. a sediment yield of 1,279 $tkm^{-2}yr^{-1}$), and 462,566 tons (i.e.a sediment yield of 1,533 $tkm^{-2}yr^{-1}$), respectively. A side from lithology and landuse/land cover, another cause for such a high rate may be the proximity of sediment source areas to riverbeds. In this manner a large share of the sediments produced by gross erosion on hillslopes reach the riverbed much faster because the storage time decreases considerably (Milliman & Meade, 1983; Walling, 1983; Milliman & Syvitski, 1992; Ferro & Minacapili, 1995; Lane & *alii*, 1997). Sediment yield values ranging from 150,000 to 250,000 tyr^{-1} are specific for the middle and lower Caşin river basins (179,881 tyr^{-1}, and 837 $tkm^{-2}yr^{-1}$, respectively), Tazlăul Sărat basin (190,404 tyr^{-1}, and 1,548 $tkm^{-2}yr^{-1}$, respectively), Tazlău upper basin (209,812 tyr^{-1}, and 1,520 $t/km^2/yr$, respectively), Tazlău lower basin (154,394 tyr^{-1}, and 1,119 $t/km^2/yr$, respectively), and the basins of left side tributaries of Trotuş river, downstream of the confluence with Tazlău river (230,420 tyr^{-1}, and 801 $t/km^2/yr$, respectively). The opposite situation, whereby the sediment yield rate is lowest (under 3,000 tyr^{-1}), is encountered in some catchments from the upper Trotuş basin, covered predominantly by woodlands. These basins, albeit overlying rocks with moderate resistance to erosion, produce a lower sediment yield due to the local topography (i.e., much lower slope gradients compared to Trotuş midcourse) and more appropriate landuse. The results we obtained partially confirm the theory which states that generally the sediment yield is inversely proportional to the size of the drainage basin (Walling, 1983). In some basins this relation is valid; however, in other instances it was not confirmed. This may be caused by certain local conditions, such as lithology, landuse, topography, climate etc, which can alter the general rule. For example, Dedkov & Moszherin (1992) studied 1,872 mountain rivers worldwide and they stated that where hillslope erosion is the main sediment source, the sediment yield is inversely related to the catchment area (i.e., increases as the basin area decreases), whereas where channel and bank erosion are dominant, the sediment yield accrues as the basin area increases. Walling & Webb (1996) conclude that in drainage basins strongly affected by human intervention hillslopes are the main sediment source area, and in this case we can infer an inverse relation between the sediment yield and drainage basin area. Likewise, Dedkov (2004) studied 352 drainage basins across Europe and concluded that the inverse relation established between the sediment yield and the basin area is specific for regions which were subjected to significant human intervention (agriculture, mining and forestry activities). In basins which were less affected by human activity a direct relation between the sediment yield and catchment area was documented. In the same context Jiongxin & Yunxia

FIG. 4 - Sediment yield and sediment delivery ratio map.



(2005) and de Vente & Poesen (2005) introduce examples which demonstrate that the sediment yield increase at first, and then subsequently decreases along with the area of drainage basins depending on the lithology of substrate and surface deposits, on the transformations undergone by the basin in time and space etc.

The sediment delivery ratio in Trotuş drainage basin

The two parameters estimated previously were employed to compute the sediment delivery ratios for catchments included in Trotuş drainage basin. Of the large amount of data derived for each catchment we retained solely those corresponding to basins above 5th order, shown in fig. 4 and table 3. The analysis of these data led to the following conclusions:

(i) the lower the drainage basin order, the higher the sediment delivery ratio; namely, in basins located on Trotuş river uppercourse the sediment delivery ratio is as high as 50% of the amount of material eroded in the basin. Moreover, smaller-sized, lower order basins, do not have the capacity to retain displaced sediments, such that they are evacuted into the higher order drainage network to a very large extent (60-70%) (fig. 5). Nakamura & *alii* (1995) compiled a synthesis of the main studies on the relation between sediment yield/sediment delivery ratio. The data presented in the study confirm a general trend according to which, in most instances, the sediment delivery ratio declines as the drainage basin area increases (Birkin-

TABLE 3 - Values for sediment yield and delivery within Trotuş drainage basin

Drainage basin	Drainage area (km^2)	Sediment yield (tyr^{-1})	Specific Sediment yield ($tkm^{-2}yr^{-1}$)	Sediment delivery ratio (%)
Trotuş - Goioasa	792	53743	191,5	22,6
Trotuş - Tg. Ocna	1965	193249	283,5	15,3
Trotuş - Adjud	4350	2257214	393	7,6
Valea Rece	121	5368	45,1	40,8
Sulţa	118	5480	44,8	21,8
Ciobănuş	136	5954	44,4	41,6
Asău	208	68914	351,6	28
Uz (upstream Uz Lake)	131	10144	63,4	57,6
Dofteana	110	27139	245	19,9
Slănic	126	27353	224,1	18,2
Oituz	337	81688	310,6	24,7
Caşin (upper course)	111	34049	267	21,2
Caşin (lower course)	308	179881	837	30,2
Tazlău (upper course)	74	209812	1520	29,3
Tazlău (middle course)	424	323896	1279	24,7
Tazlău (lower course)	1104	154334	1119	13,5
Tazlăul Sărat	210	190404	1548	29,9

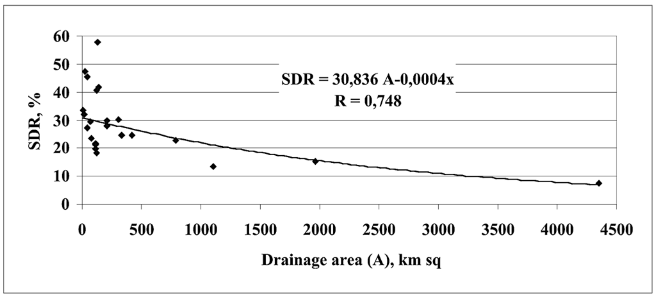


FIG. 5 - Sediment delivery ratio related to drainage basin area.

shaw & Bathurst, 2006). In basins with areas ranging from 2,000 to 7,000 km^2 the sediment delivery ratio is commonly around 4%, whereas in basins smaller than 100 km^2 nearly half of the amount of material eroded in basin is evacuated from the basin. Similar conclusions regarding this inverse relation were reported by Strand & Pemberton (1987), Morris & Fan (1997) for drainage basins from USA, Avendaño & *alii* (1997) who used measurements made on 60 reservoirs in Spain, whereby the areas of drainage basins ranged from 31 km^2 to 17,000 km^2. They explain that as the basin area augments, the slope and channel gradients decrease (along with the sediment transport energy), which in turn favors sediment deposition in channel beds. Therefore, the distance between the hillslope sediment source areas and the channel increases (which leads to a decrease in the sediment delivery ratio) and localized storms (which cause erosion) have proportionally smaller spatial effect.

(*ii*) The decrease in the sediment delivery ratio is inversely related to the drainage network order and the size of drainage basins (Ichim, 1988; Ichim & *alii*, 1986, 1992). Large basins such as Oituz, Tazlău, Caşin have sediment delivery ratios below 30%, thus the eroded sediment storage capacity increases. These results are similar to the outcome of studies by Rădoane & Ichim (1987) and Ichim (1987, 1990), who studied drainage basins from the Flysch Mountains and the Moldavian Tableland and showed that within same order basins, lithology is the main factor leading to variations in the magnitude of both gross erosion (4 times higher in the Subcarpathian area) and sediment delivery (approx. 1,5 higher in the Subcarpathian area). One of the causes for this situation is likely linked to geomorphology, namely, the broad extension of areas affected by landsliding and gully erosion, which transfer hillslope deposits towards river channels, whereas the high percentage of clay within the lithological composition of this region results in the removal of a larger amount of sediments. In drainage basins above 5th order an attenuation of differences in the magnitude of the sediment delivery ratio in the two types of lithology (i.e., flysch and molasse) has been documented.

(iii) The values of the sediment delivery ration reveal the increasingly larger sediment storage as we near the junction with Siret river. Thus, in Lunca de Sus gauging station (located 14 km from the headwaters) the sediment delivery ratio is as high as 40%, as compared to 23% in Goioasa (54 km from the headwater), 15% in Târgu Ocna (90 km from the headwater), and just 7.6% of the total amount of eroded sediment evacuated annually in the drainage basin outlet. These results are consistent with those reported in the literature (Roehl, 1962; Williams & Berndt, 1972; Malmon & *alii*, 2005; Lu & *alii*, 2005; Alatorrea & *alii*, 2010; Porto & *alii*, 2011; Lopez-Tarazon & *alii*, 2012), according to which there is an inverse relation between SDR and the drainage basin area (fig. 6).

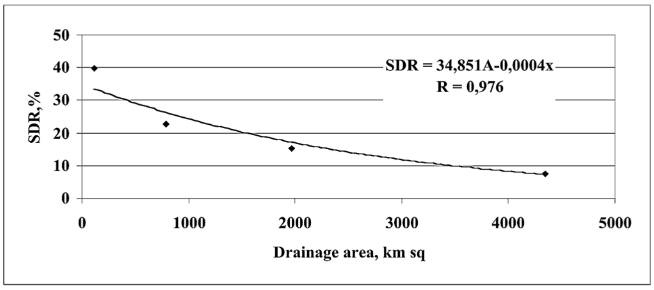


FIG. 6 - Sediment delivery along the Trotus River.

CONCLUSIONS

In order to determine the sediment delivery ratio in Trotuş drainage basin a set of regression equations were used for each of the three relevant lithological groups classified according to their resistance to erosion. By applying these equations we determined that 80% of the gross erosion occurs in the areas comprising of rocks with low resistance to erosion which account for 40% of Trotuş basin area. Moreover, the values estimated for the sediment delivery closely reflect the lithological composition of the substrate. As expected, the highest rates were documented in areas with rocks with lower resistance to erosion (molasse and avant fosse areas), which also coincide with the regions where the anthropogenic intervention on hillslopes has been strongest. The values of the sediment delivery ratio fall within the general range of values reported in other drainage basins evolving under similar natural conditions. In basins from the Subcarpathian sector or overlying Quaternary deposits, local factors such as topography, climate conditions, landuse/land cover and the occurrence rocks with low resistance to erosion, enhance erosion and as a result the sediment yield ranges from 150,000 to 500,000 t/yr, whereas the sediment delivery ratio amounts to 80% in 3rd order basins, and 30% in 4th order basins, respectively. In drainage basins from the flysch area, despite the rather significant runoff and high speed of streams in 4th and 5th order basins, the occurence of resistant rocks and the more adequate use of terrains resulted in lower rates for gross erosion, sediment yield, and subsequently for the sediment delivery ratio. Of the entire amount of sediments eroded in Trotuş drainage basin only 7.6% are discharged into Siret river. Thus, we can conclude that the sediment delivery ratio in Trotuş drainage basin is inversely proportional to the drainage network order and to the size of the basin area. By comparing these results with direct measurement data from selected gauging stations, they can be considered acceptable, taking into account that only the suspended sediment load is recorded, but not the bed load.

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