

The temporal variation of suspended sediment transport according to the dominance of suspended sediment sources. Case study: the Trotuș river between 2000 and 2014

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Abstract

Based on the data series of average daily streamflow and suspended sediment load recorded between 2000 and 2014 at four gauging stations (Lunca de Sus, Goioasa, Târgu Ocna and Vrânceni), the temporal variation of the suspended sediment transport was investigated according to the prevalence of source areas. Thus, a significant temporal variability (monthly, seasonal, annual) was determined, in close relation with the amount of precipitation and the streamflow. The following equation was determined between the mean monthly suspended sediment load ($\bar{R}$) and the mean discharge ($\bar{Q}$) at Vrânceni section: $R = 0,0035Q^{2,2895}$, $r = 0,899$. We believe this relation has a high degree of confidence for the indirect determination of solid load and it is comparable with other equations of this type. Along the entire length of the river, July was the month during which the highest suspended sediment load was recorded, with an average percentage of 37% of the total amount. At the opposite end, December is the month with the lowest documented suspended sediment load, with just 0.5% of the total amount transported annually by the Trotuș. As regards the seasonal variability of the suspended sediment load, the following values were determined along the entire length of river Trotuș: during the winter season the volume of sediment carried by the river amounts to approx. 2.1% of the total annual transported suspended sediment, the spring season accounts for 33.7% of the annual volume, the summer season accounts for ca. 55.5%, and the fall for 8.7%. In order to plot the R-Q correlation, the wettest, as well as driest years were selected for every gauging station. On the resulting plots, there were identified the thresholds based on which the two sources were separated depending on the area of origin: dominant from the catchment or dominant from the river bed. Overall, during the investigated period on the Trotuș river, the river beds contributed with about 21% of the total volume of transported suspended sediment. Depending on the type of the year (wet, dry or normal), the average input of the beds to the annual volume of suspended alluvium was as follows: 4% in wet years; 43% in dry years; 15% in normal years. The total volume of suspended sediment transported through the four sections on the Trotuș river between 2000 and 2014 amounted to approx. 39x10⁶ t, thus the average annual volume was 2,598,000 t. A large share of this suspended sediment yield was produced during major floods. For example, at Vrânceni ca. 61% of the total sediment yield for the 15 year-period under investigation resulted from just 3 flood events (2005, 2010 and 2012).

Keywords: *Suspended sediment, temporal variation, sediment sources, suspended sediment yield*

Rezumat. Variația temporală a transportului de aluviuni în suspensie în funcție de dominanța ariilor sursă. Studiu de caz: râul Trotuș în perioada 2000-2014

Pe baza datelor referitoare la debitele lichide și solide în suspensie medii zilnice, înregistrate în perioada 2000 - 2014 la patru stații hidrometrice (Lunca de Sus, Goioasa, Târgu Ocna și Vrânceni), s-a identificat variația temporală a transportului de aluviuni în suspensie, în funcție de dominanța ariilor sursă. Astfel, a fost pusă în evidență o însemnată variabilitate temporală (lunară, sezonieră, anuală), strâns corelată cu cantitatea de precipitații și debitele lichide. Între debitul solid în suspensie mediu lunar ($\bar{R}$) și debitul lichid mediu ($\bar{Q}$), în secțiunea Vrânceni, s-a obținut relația: $R = 0,0035Q^{2,2895}$, $r = 0,899$. Noi o considerăm o relație cu grad înalt de încredere pentru determinarea indirectă a debitelor solide, fiind comparabilă cu alte relații de acest tip. În perioada avută în studiu, pentru întreg râul Trotuș, luna cu cel mai mare transport de aluviuni în suspensie a fost iulie, cu o pondere medie de circa 37% din total. La polul opus se află luna decembrie, care nu deține decât 0,5% din totalul aluviunilor în suspensie transportate de către râul Trotuș. În privința variabilității sezoniere a debitului de aluviuni în suspensie, la nivelul întregului râu Trotuș, au fost obținute următoarele valori: în timpul sezonului de iarnă au fost transportate circa 2,1% din volumul total al aluviunilor în suspensie; în sezonul de primăvară 33,7%; sezonului de vară i-au revenit circa 55,5%, iar celui de toamnă, 8,7%. Pentru construcția graficului corelației R-Q au fost selectați, la fiecare stație hidrometrică în parte, anii cei mai ploioși și cei mai secetoși. Pe aceste grafice au fost identificate pragurile în funcție de care s-au separat cele două surse după aria de proveniență: dominantă din bazinul versant și dominantă din albie. Pe ansamblul râului Trotuș, în perioada studiată, albiile au contribuit cu circa 21% din totalul volumului de aluviuni în suspensie tranzitate. În funcție de tipul anului (ploios, secetos, normal), situația este următoarea: în anii ploioși media de contribuție a albiilor a fost de 4%; în anii secetoși de 43%, iar în anii normali de 15%. Volumul total de aluviuni în suspensie tranzitat prin cele patru secțiuni hidrometrice din lungul râului Trotuș, în perioada 2000-2014, a fost de aproximativ 39x10⁶ t, de unde rezultă o medie anuală de 2 598 000 t. Mare parte din această producție de aluviuni în suspensie a fost realizată în timpul marilor viituri. De exemplu, în secțiunea Vrânceni, circa 61% din totalul producției de aluviuni pentru cei 15 ani avuți în studiu a fost realizată în timpul a doar 3 evenimente de viitură (2005, 2010 și 2012).

Cuvinte-cheie: *aluviuni în suspensie, variație temporală, surse de aluviuni, producție de aluviuni în suspensie*

Introduction

Knowing the temporal variability of suspended sediment transport and suspended sediment yield (SSY) is required for various purposes, which include: designing erosion control works (Russel et al., 2001; Walling, 2005); river morphological computations and evaluation studies of the effects of various land use management practices (Gao and Puckett 2011; Yeshaneh et al., 2014); siltation of downstream reservoirs (Rădoane and Rădoane, 2005; Guzman et al., 2013). *"Information on sediment source is of fundamental importance in understanding the suspended sediment dynamics and the sediment budget of a catchment. Information on sediment source also represents a key requirement from the management perspective, since identification of sediment sources is a key precursor to the design of effective sediment management and control strategies"* (Walling, 2005).

The volume of suspended sediment carried by a river during a wet period is significantly larger compared to the amount transported during a dry period due to the net difference in the soil structure and moisture level between the two periods. Differences also exist in terms of the number, intensity and duration of precipitation (Xia, 2010).

The aim of this study is to analyze the trend of the suspended sediment transport at various temporal scales (monthly and seasonal, annual or during flood events), depending on the prevailing source areas during that particular timeframe (either riverbed or slopes).

Study area

Trotuș drainage basin is located in the central-eastern sectors of the Eastern Carpathians and Moldavian Subcarpathians (Fig.1). The total area of the basin is 4350 km², whereas the length of the Trotuș river is approx. 160 km. The average long-term precipitation amounts to approx. 800 mm basin-wide, varying by ± 200 mm in the high mountain areas compared to lower areas.

The interaction between the physical geographical traits of the study area and the circulation of air masses results in deviations in the distribution of monthly and annual precipitation. Such was the case in 2005, when the precipitation recorded during the 11th-13th of July accounted for 100-150% of the multiannual average of July (Dumitriu, 2007; Romanescu and Nistor, 2011). The average multiannual discharge from the Trotuș river ranges from 0.9 m³ s⁻¹ in the upper course (Lunca de Sus gauging station) to 35 m³ s⁻¹ in the lower course (Vrânceni gauging station). Except for the gauging sites on the upper course of the Trotuș (Lunca de Sus and Ghimeș Făget), for which the highest peak

discharge values were recorded between 1975 and 1985, the stations recorded the highest peak discharges in 2004-2005. Discharge values recorded in 2005 are considered exceptional historical values, with an Average Recurrence Interval (ARI) of 200 years. The highest peak discharge on the river Trotuș is considered to be the value recorded in 2005 (2845 m³ s⁻¹ at the Vrânceni gauging station), rather than the 3720 m³ s⁻¹ value recorded on the 29th of July, 1991, because the latter was not entirely generated by natural causes and was due in part to the failure of Belci dam (Podani and Zăvoianu, 1992).

The rise in the peak discharge values post-2000 can be attributed to the increasing amount of precipitation over a very short period of time.

In the Siret river basin, the percentage of precipitation related to the total sum of the maximum amounts of precipitation falling during a 24 hour period, with a value above 100 l m⁻², has steadily increased (8.3% between 1941-1960, 30.8% between 1961-1980, 47.5% during 1980-2000 and 67.7% after 2000) (Pleșoianu and Olariu, 2010). This could be a valid argument for the present situation, in which, of the top four peak discharge values recorded at the Vrânceni gauging station (during 64 years), two occurred during the study period (2845 m³ s⁻¹ - 2005; 1700 m³ s⁻¹ - 1975; 1567 m³ s⁻¹ - 2010; and 1510 m³ s⁻¹ - 1988).

The distribution of soil types (especially of those susceptible to erosion) is of particular importance to studies regarding the suspended sediment load. Conjunctly, Cambisols and Luvisols cover over 75% of the total area of Trotuș river basin; of these, Cambisols account for the largest area (53.35% of the basin area) divided among soil classes as follows: *eutricambosols* – 24.84% (occurring at 60 to 1000 m a.s.l. in Asău basin, along the Trotuș upstream of the junction with Asău, as well as in small catchments such as Ciobănuș, Sultă, Șugura, Ciugheș, Tărhăuș, Valea Rece etc); and *districambosols* – 28.51% (found at 1000 to 1400 m a.s.l., predominantly in mountain areas such as the Nemira, Goșmanu, Tarcău and Ciuc Mountains). Noteworthy is the frequent occurrence of *erodosols* within the Subcarpathian area which reveals the active presence of current geomorphological processes. The typical distribution of soils according to latitudinal location and elevation is disturbed by the presence of *aluvisols* which are prevalent along river floodplains (9.46%).

The banks of the Trotuș river are typically sandy (over 70% in most instances); however, between confluences the percentage of silt and clay increases (up to 40% at Belegheț and Perchiu, 32% at Burcioaia, 30% at Comănești) (Dumitriu, 2007; Dumitriu et al., 2011).

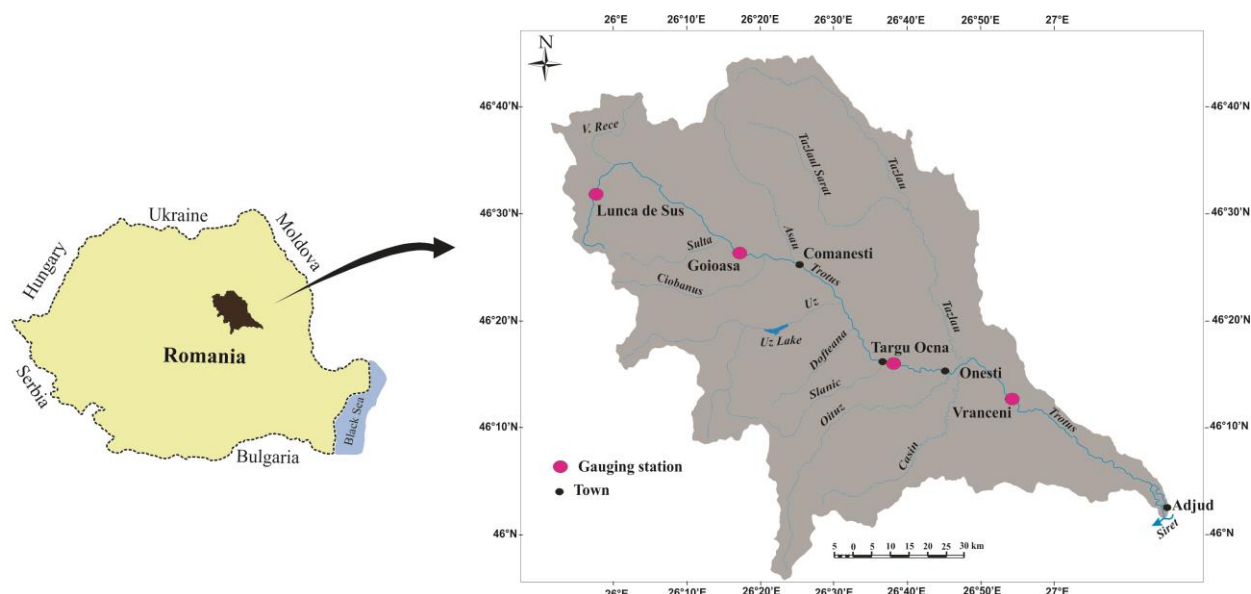


Fig. 1: Study area

Data and methods

The temporal variation of the suspended sediment load and the prevalence of source areas were investigated based on data series of daily, monthly and annual average values of the streamflow and suspended recorded load between 2000 and 2014 at four gauging stations: Lunca de Sus (146 km from the confluence, area of the drainage basin – 88 sqkm), Goioasa (106 km – 781 sqkm), Târgu Ocna (69 km – 2091 sqkm) and Vrancea (37 km – 4092 sqkm) (Fig.1). These data were processed using statistical indicators of data distribution (average, median, modulus, standard deviation, coefficient of variation etc.).

The problem of sediment sources according to the area of origin was addressed using the methodology introduced by Grimshaw and Lewin (1980) based on the $R = f(Q)$ equation, which takes on different forms depending on the season and the size of transported material, resulting in high scattering which can suggest the following (Rădoane and Rădoane, 2003, 2007):

a) the upper limit of the graph indicates summer discharge when the sediment load and streamflow are high and the alluvium originates mainly in the catchment;

b) the lower limit of the graph typically indicates fall-winter discharge when the sediment load comes mainly from the river bed.

The investigated period (2000-2014) was chosen due to the observed trend of significant increase in the suspended sediment load, particularly along the mid- and upper course (Fig.2). Thus, at Târgu Ocna gauging station, the multiannual mean value of the

suspended sediment load was 14.6 kg/s from 1950 to 2000, whereas between 2000 and 2014 the average was 34.8 kg/s. The same tendency was documented at Goioasa and Lunca de Sus stream gages, whereby the mean multiannual suspended sediment load was 2 to 3 times higher between 2000 and 2014 compared to the previous interval, 1950 to 2000.

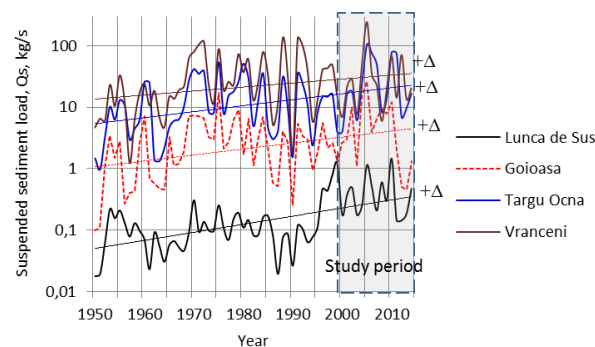


Fig. 2: Trends of annual mean suspended sediment load

Wet or dry years were determined based on the following equation:

$$(Q_{myr} - Q_{mmyr}) / Q_{mmyr} \quad (1)$$

where Q_{myr} is the average discharge for one year, and Q_{mmyr} is the mean multiannual discharge. If the value is positive, the respective year is considered wet; conversely, when it is negative the year is classified as dry. Throughout the study period just three years rank as wet (i.e. 2005, 2006 and 2010), whereas 2000, 2001, 2003, 2007, 2012, 2013 are dry, and the remaining ones are considered normal.

Results and discussions

Temporal variability (monthly, seasonal, annual) of suspended sediment load

Both the streamflow and the suspended sediment load are highly variable over time. Between 2000 and 2014 the mean values of the suspended sediment load on the Trotuș river ranged from 2274 kg/s at an average monthly discharge of 234 m³/s in July 2005 at Vrânceni streamgauge to just 0.001 kg/s at an average monthly discharge of 0,285 m³/s in January 2000 at Lunca de Sus. The years whereby the highest sediment load was recorded were 2005, 2012 and 2010; during the same years the annual volume of suspended sediment (Qs) at Vrânceni gauging station was 7,769,760 t in 2005, 2,274,330 t in 2012 and 2,191,511 t in 2010. The peak value which coincides with the historical value) of 52,500 kg/s (at a discharge of 2845 m³/s) was recorded at Vrânceni gauging station on the 13th of July 2005.

The suspended sediment load values mostly fall into the general trend documented on rivers from the temperate zone. Along the entire length of the river, between 2000 and 2014, July was the month

during which the highest suspended sediment load was recorded, with an average share of 37% of the total amount (Fig.3.A). This is a consequence of the number and magnitude of flood events occurring in July (in 2004, 2005, 2010) which boosted the transport of alluvia. Conversely, December is the month during which the lowest suspended sediment load was documented, with just 0.5% of the total amount transported annually by the Trotuș river.

The mean monthly suspended sediment load at the four gauging stations show the same trend observed along the entire river length (Fig.3.B). For example, at Vrânceni streamgauge ca. 47% of the total amount of suspended sediment was transported in July, whereas the share of suspended sediment carried in January, February, November and December is, with little exception, below 1%. This only applies for the investigated period; throughout time, the month with the largest amount of transported suspended sediment varied depending on major flood events. Thus, floods occurring in certain months have decisive influence on the multiannual monthly variation of the suspended sediment load.

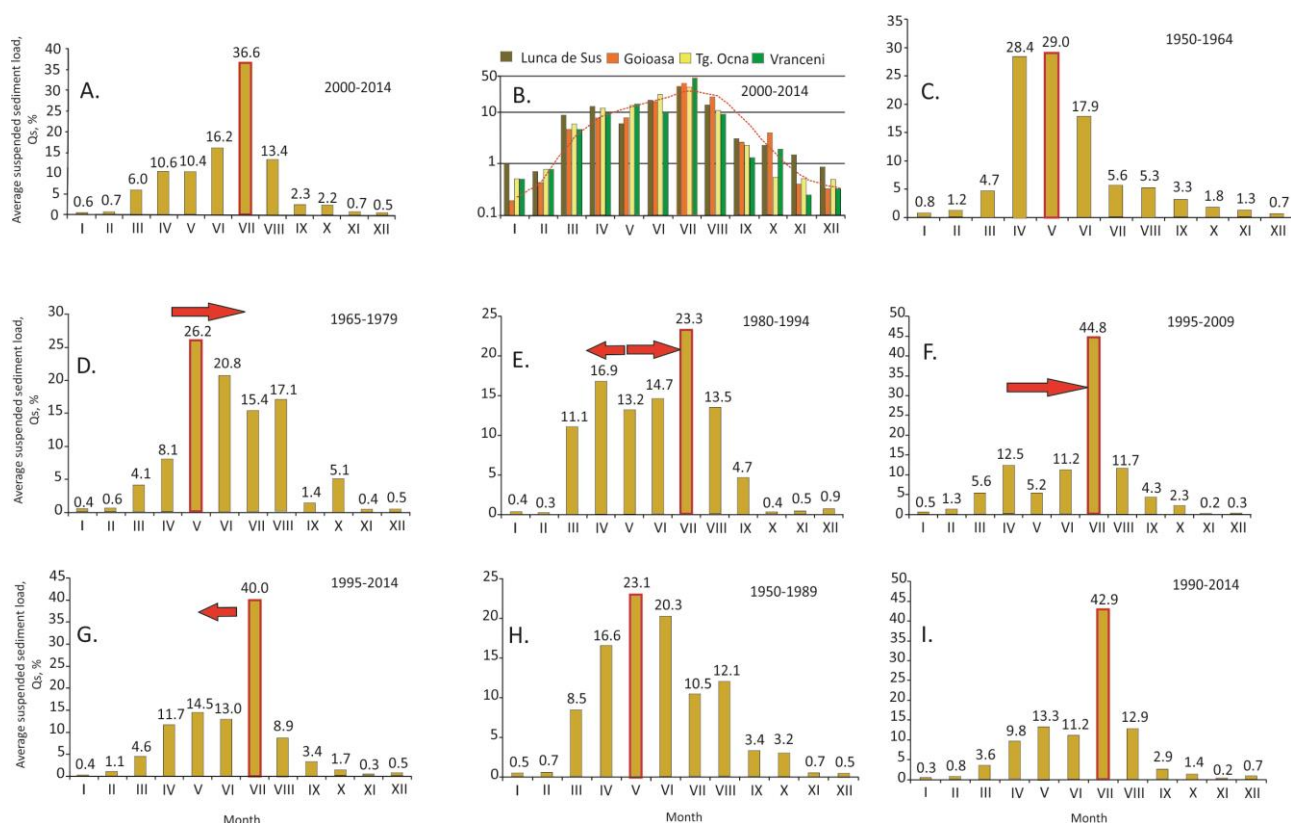


Fig. 3: Variability of monthly percentage of suspended sediment load: (A) average for the Trotuș river; (B) average at every gauging station; (C) average from 1950 to 1964 at Vrânceni gauging station; (D) average from 1965 to 1979 at Vrânceni gauging station; (E) average from 1980 to 1994 at Vrânceni gauging station; (F) average from 1995 to 2009 at Vrânceni gauging station; (G) average from 1995 to 2014 at Vrânceni gauging station; (H) average from 1950 to 1989 at Vrânceni gauging station; (I) average from 1990 to 2014 at Vrânceni gauging station

A major flood event during which large amounts of alluvia were transported will remain imprinted in the monthly trend of the suspended sediment load until a new event of similar magnitude will succeed in changing the old monthly distribution. Between 1950 and 1979, the month of May held the largest share of the amount of transported suspended sediment due to the fact that for ca. 30 years the largest floods (1953, 1960, 1961, 1965, 1970, 1971, 1975) occurred during this month (Fig.3.C and D).

From 1980 to 1994 a double shift was documented: at the beginning of the interval, flood events tended to concentrate in March-April, thus resulting in the increasing share of April and March (continued through the floods in 1984, 1988 and 1993), while the share of May was still high (due to the floods in 1981 and 1993); towards the end of the interval the largest share of suspended sediment transport shifted to July and August as an effect of the flood events in 1991 and 1992 (Fig.3.E). After 1995, the flood events from 1997, 2004 and particularly 2005 were instrumental in establishing July as the month during which the largest amount of suspended sediment is carried through the river channel (45%) (Fig.3.F) for over 20 years. After 2009, a slight decrease of the share of July was documented, conjunct with increasing shares of April, May and June, as a result of the flood events of 2010 and 2012 (Fig.3.G). In terms of the month with the largest share of transported suspended sediment, at Vrânceni two separate phases can be distinguished: between 1950 and 1989, the month

with the highest percentage was May, albeit the values were nearly uniformly distributed from March until August; however, after 1991 the transport of suspended sediment has become overly concentrated in July (Fig.3.H and I).

As regards the seasonal variability of the suspended sediment load, between 2000 and 2014 the following values were determined along the entire length of the Trotuș river: during the winter season (months I, II and XII) the volume of sediment carried by the river amounts to approx. 2.1% of the total annual transported suspended sediment, the spring season (months III-V) accounts for 33.7% of the annual volume, the summer season (months VI-VIII) accounts for ca. 55.5%, and the fall (IX-XI) for 8.7%. During the winter season, when the substrate is typically frozen, the suspended sediment load ranged between 14.3% at Târgu Ocna gauging station (in the winter of 2009) and 0.028% at Goioasa streamgage (2005) (Fig.4.A). In some years, spring thaw is accompanied by abundant rainfall, which results in the significant increase of the volume of transported suspended sediment. This phenomenon is clearly visible in dry years, when the alluvium transported during the spring season can amount to as high as 90% of the total annual volume; e.g., in 2012 the suspended sediment load recorded during the spring months at Târgu Ocna and Vrânceni gauging stations accounted for 91%, and 98%, respectively, of the annual volume. Values exceeding 80% were reported in 2000 and 2004 at Lunca de Sus (Fig.4.B).

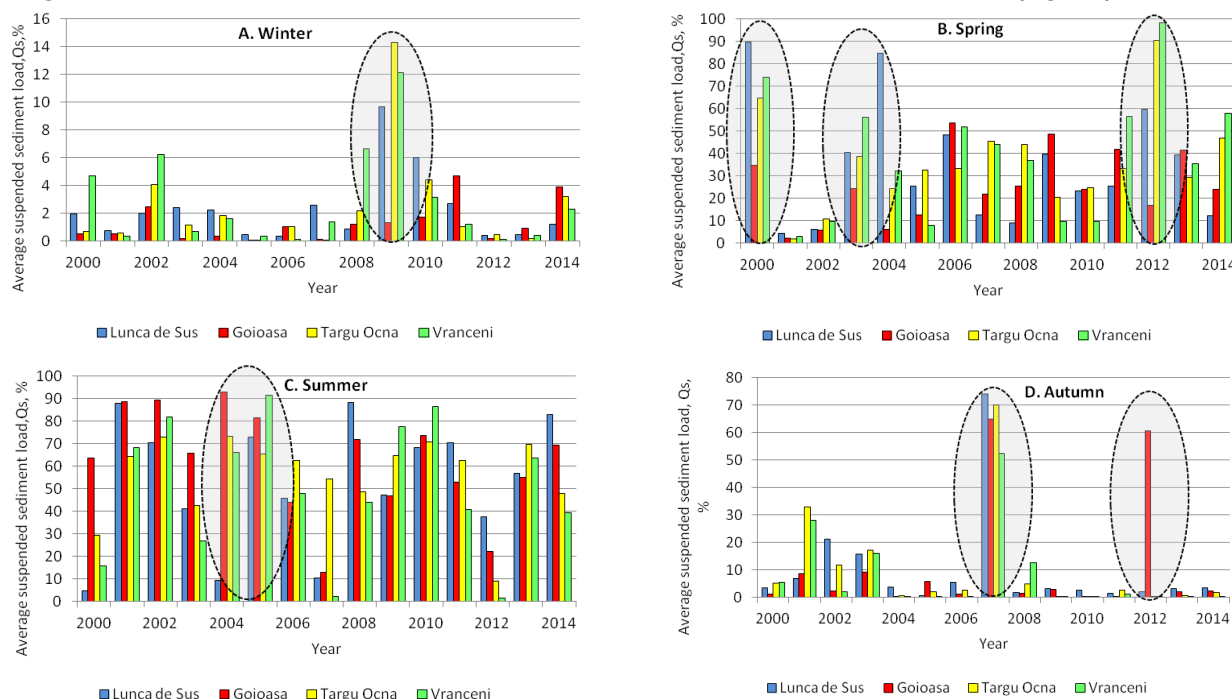


Fig. 4: Distributions of suspended sediment discharges during four climatic seasons at four sediment stations along the Trotuș River, 2000-2014 water years

The summer season accounts for the largest share of the total annual amount of suspended alluvium, particularly as an effect of major floods; in-between floods, however, the values of the solid load are rather low (Obreja, 2009). Within the investigated period, 2000 and 2005 stand out as the years when the percentage of the suspended sediment transported during the summer season accounted for over 90% of the total annual volume (Fig.4.C). In the fall season, the lack of major flood events resulted in low sediment loads, with the notable exception of 2007 and 2015, when the share of the sediment transported during the fall reached over 60% of the annual volume, particularly in the upper and mid-course (Fig.4.D).

From 2000 to 2014 the peak stream discharge recorded at Vrânceni gauging station was 2845 m³/s (July 13, 2005, 200 years RI). By setting class amplitude at 25 m³/s, up to 600 m³/s, 24 classes were obtained, each comprising at least one value. An additional 3 discharge values exceeding 600 m³/s (i.e. 769 m³/s; 1468 m³/s și 2845 m³/s) were ranked in a single 25th class "above 600 m³/s".

During the three flood events whereby the peak discharge exceeded 600 m³/s, 26% of the entire suspended sediment load measured in the 15-years period was transported (approx. 25x10⁶ t).

On July 13, 2005, only, no less than 4.5 x10⁶ t of suspended sediment were transported, accounting for 18% of the entire amount. Based on these data, the 1122 m³/s discharge value (10 years RI) would represent the effective discharge of the Trotuș river at Vrânceni gauging station, which is rather inaccurate, as the state of the river was highly distorted by this extreme event. By excluding

stream discharge values recorded on the 12th and 13th of July 2005, we determined that the effective discharge at Vrânceni streamgage from 2000 to 2014 is 237.5 m³/s (1.2 years RI), which carries approx. 13% of the total suspended sediment load transported by the Trotuș river. The occurrence duration of this discharge value is 0.2 of the time. The average daily streamflow with the highest frequency (66%) at Vrânceni gauging station ranges between 2 m³/s and 25 m³/s; however, the amount of suspended sediment transported at these discharges is relatively low (approx. 2.1%).

The following equation was determined between the mean monthly suspended sediment load ($\bar{R}$) and the mean discharge ($\bar{Q}$) at Vrânceni section: $\bar{R} = 0.0035 \bar{Q}^{2.2895}$, $r = 0.899$. We believe this relation has a high degree of confidence for the indirect determination of solid load and it is comparable with other equations of this type.

Temporal variability of suspended sediment sources

In order to plot the R-Q correlation throughout the 2000-2014 period the wettest, as well as the driest years were selected for every gauging station. On the resulting plots, the thresholds were identified according to which the two sources were separated depending on the area of origin: *dominant from the catchment* or *dominant from the river bed*.

At Lunca de Sus streamgage, the threshold distinguishing between the two source areas was determined between 0.8 and 1.5 m³/s (Fig.5). The bed provides on average approx. 33% of the suspended alluvia, whereas the catchment supplies the remaining 67%.

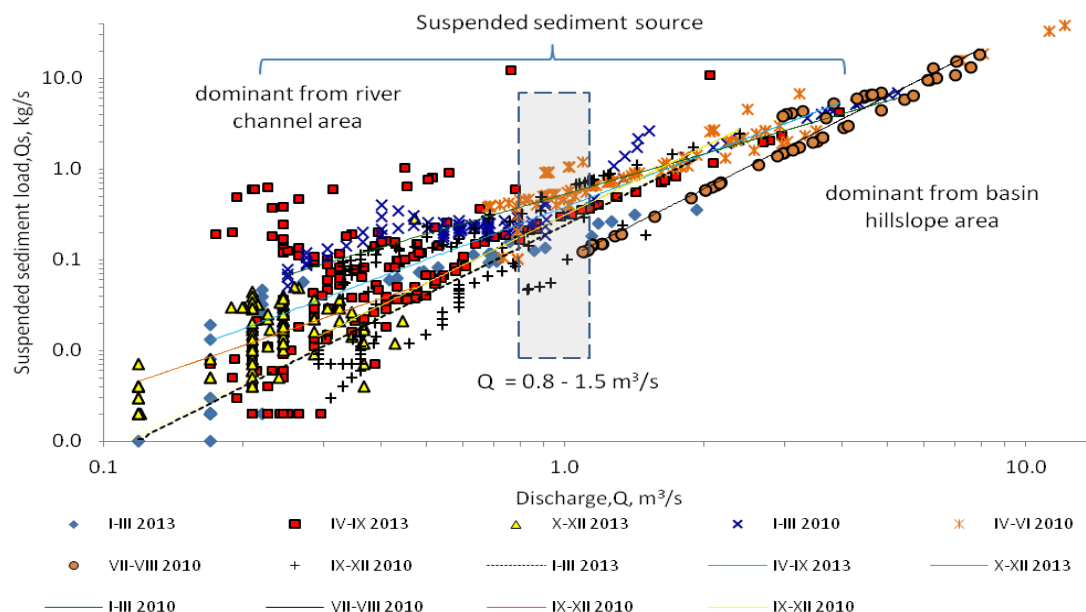


Fig. 5: Identifying sediment sources based on the mean daily suspended sediment load at Lunca de Sus gauging station

Seasonally, the parameters vary as follows: during summer, the catchment can provide on average ca. 50% of the sediment transported annually, whereas the input of the bed, albeit large in terms of sheer amount, is comparatively smaller (ca. 22%); in fall and winter the input of the slopes decreases compared to the input of the bed, which on occasion can supply as much as 100% of the alluvia transported during these seasons (although relative to the entire year, they only account for 1-3%).

Extreme events, and floods, in particular, heavily influence the size of the catchment – bed ratio: in 2013 (low precipitation and stream flow discharge), of the total 5,830 t of suspended sediment measured, 74% originated in the river bed; in 2010 (abundant rainfall and a peak discharge of 17.6 m³/s), of the total measured 46,466 t of suspended sediment, just 10% was provided by the bed.

As regards the monthly distribution, it has been noted that during winter and fall months, as well as in dry years (Fig.6), the bed provides the largest amount of alluvia, albeit this is considerably smaller in terms of volume compared to the one supplied by the catchment slopes.

At Goioasa gauging station, the threshold between the two source areas was established between 7 and 10 m³/s (Fig.7). From 2000 to 2014 the beds provided, on average, ca. 25% of the total transported suspended sediment, distributed seasonally as follows: 5.6% during the winter season; 2.93% in spring; 15.06% in summer and 1.16% during the fall. During the spring and summer seasons the catchment slopes supply approx. 77% of the total volume of suspended sediment.

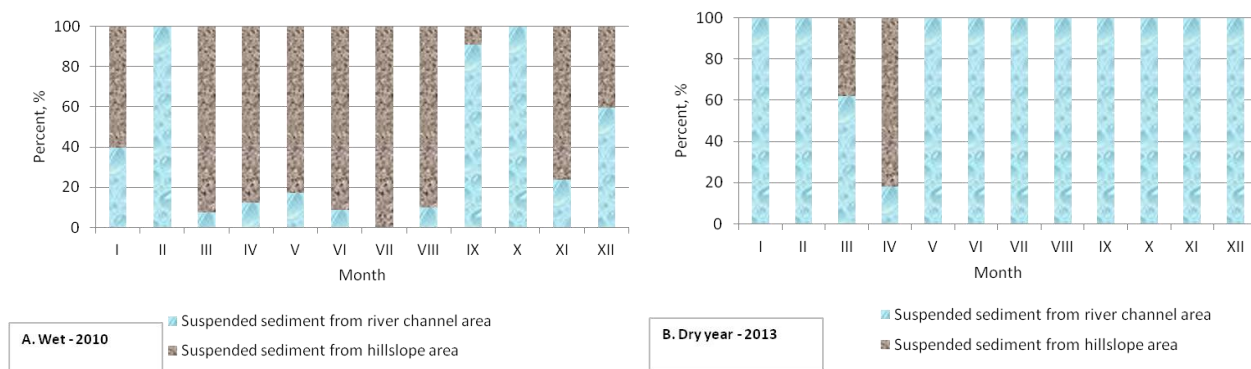


Fig. 6: Monthly percentage of sediment provided by river beds and catchment slopes at Lunca de Sus gauging station

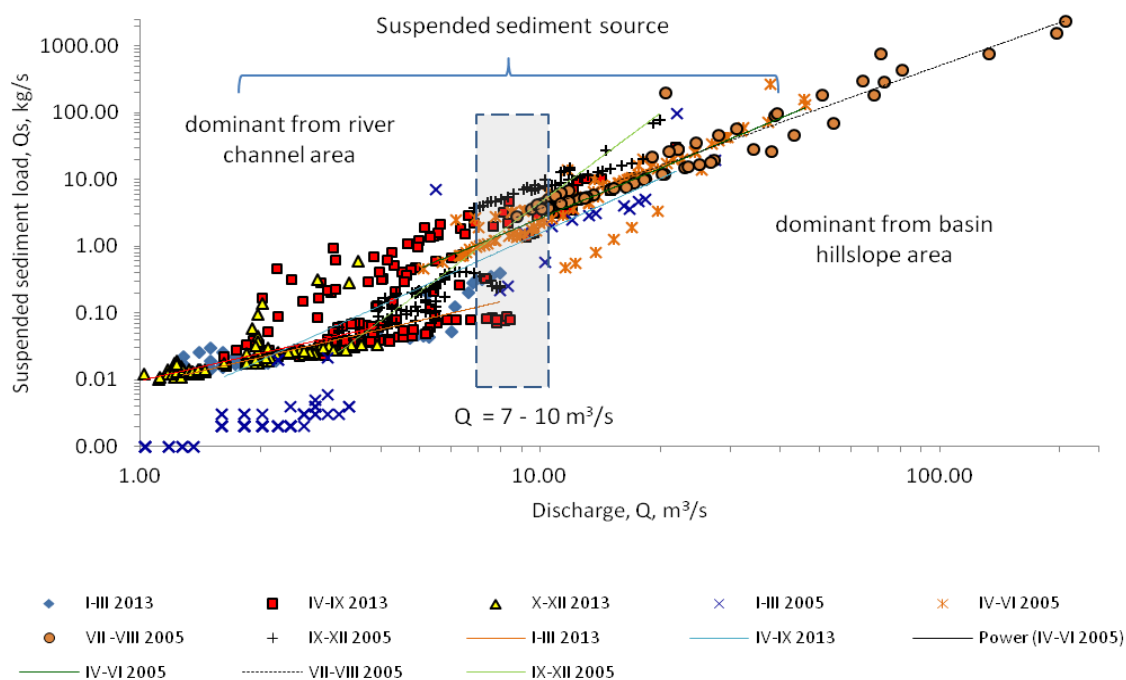


Fig. 7: Identifying sediment sources based on the mean daily suspended sediment load at Goioasa gauging station

In 2005 (wet year), the slopes provided ca. 99% of the total 852,612 t of suspended alluvia transported through Goioasa section, whereas in 2013 (dry year) the beds accounted for ca. 37% of the total amount. Two floods (2nd -5th of April and June) were able to transport 63% of the total volume of suspended sediment (14,371 t), while

during the remainder of the year the contribution of the slopes was nearly null (Fig.8).

The data recorded at Târgu Ocna section indicate that river beds provide a significantly lower amount of suspended sediment, i.e. just 18% of the total volume. At this streamgage, the threshold between the two source areas was determined between 17 and 25 m³/s (Fig.9).

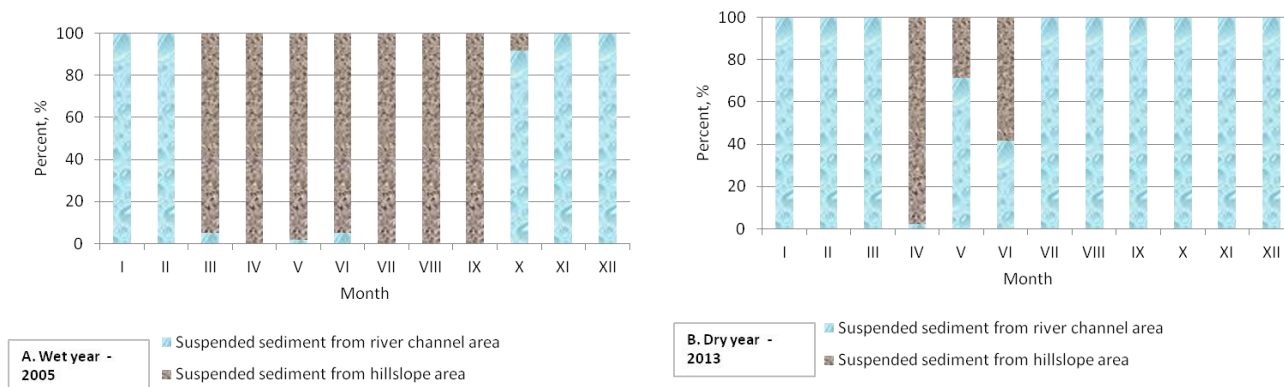


Fig. 8: Monthly percentage of sediment provided by river beds and catchment slopes at Goioasa gauging station

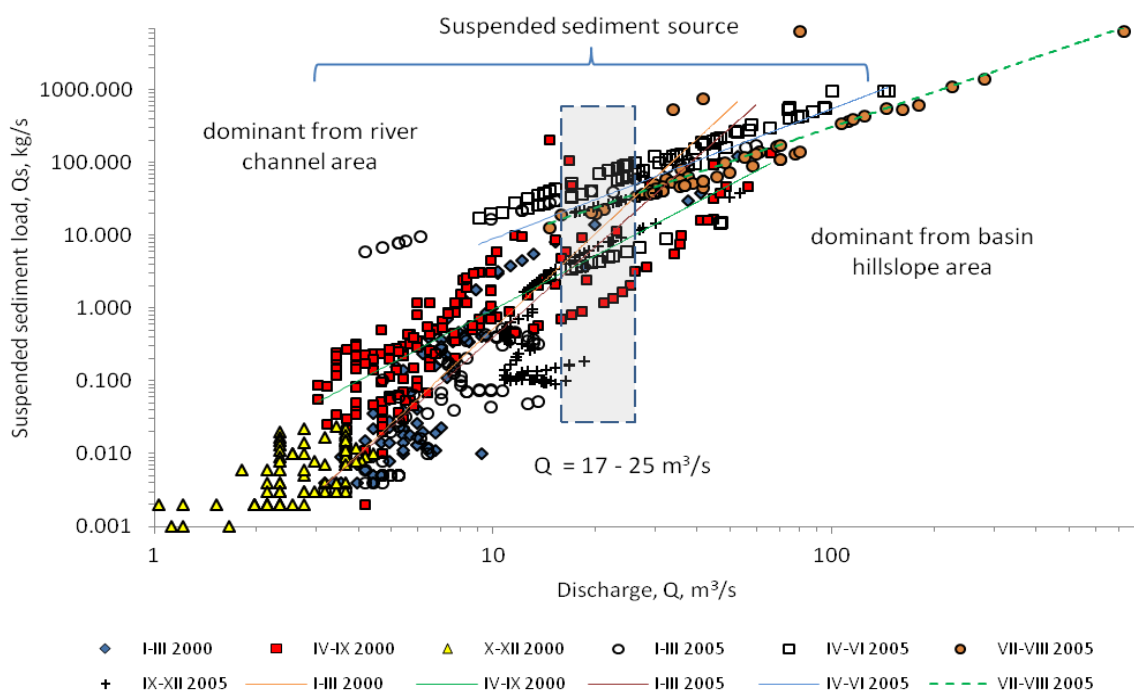


Fig. 9: Identifying sediment sources based on the mean daily suspended sediment load at Târgu Ocna gauging station

In 2005 the catchment slopes supplied 96% of the total suspended alluvia, which was estimated at 3,308,048 t; no less than 50% of this amount was transported in July. In 2000 (dry year) the river beds provided approx. 40% of the total volume of suspended sediment carried by the Trotuș river through Târgu Ocna section; moreover, for 8 months of 2000 the beds provided the majority of the suspended alluvia. In a normal year (e.g.,

2002), the beds account for approx. 15% of the sediment load.

At Vrânceni gauging station, where the separation threshold was established between 30 and 50 m³/s (Fig.10), the contribution of the river beds to the suspended sediment load is ca. 11%. However, it has been observed that the amount of sediment supplied by the beds remains constant, in general, regardless of the water year (wet, dry or normal), ranging from 80,000 to 100,000 t. In a wet

year, such as 2005, during summer the catchment slopes deliver approx. 91% of the total volume of suspended alluvium transported throughout the year, whereas in a dry year (e.g. 2013), their percentage decreases to 40-50%. In 2013 ca. 60% of the total amount of sediment was transported in just a few days in July. Overall, during the

investigated period on the Trotuș river, the river beds contributed to about 21% of the total volume of transported suspended sediment. Depending on the water year (wet, dry or normal), the average input of the beds to the annual volume of suspended alluvia was as follows: 4% in wet years; 43% in dry years; 15% in normal years.

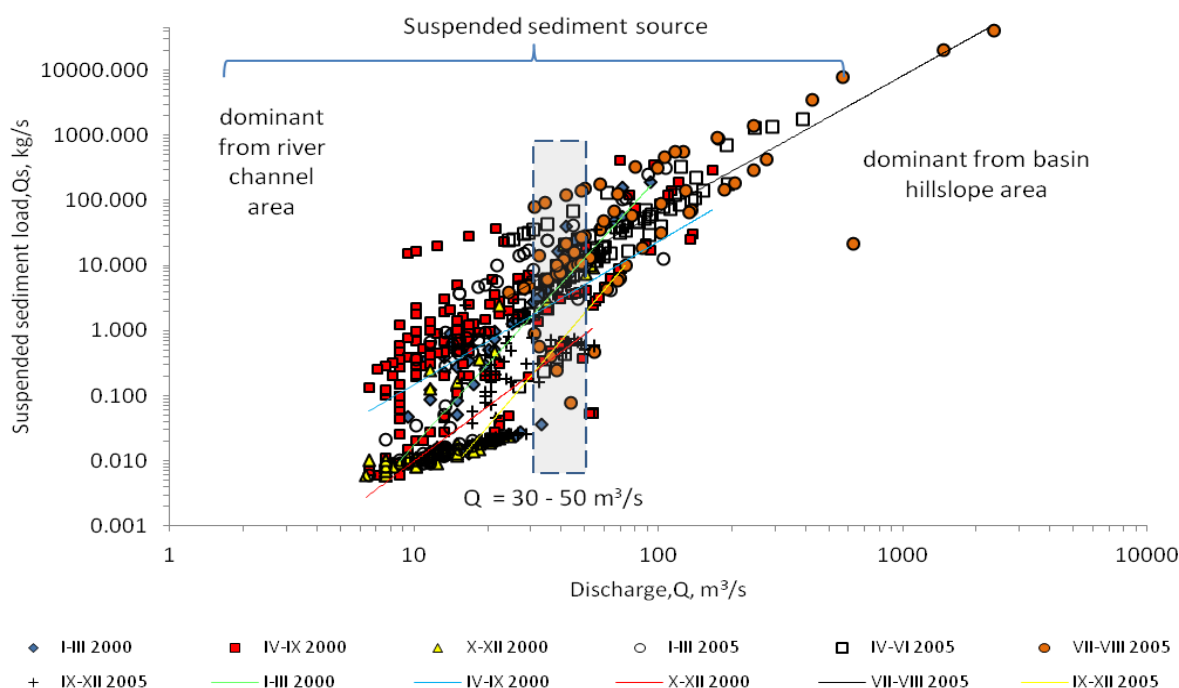


Fig. 10: Identifying sediment sources based on the mean daily suspended sediment load at Vrânceni gauging station

Sediment yield

Hicks et al. (1996) has indicated that the main factors affecting regional variation in sediment yield are basin mean annual rainfall and, to a lesser and more contentious extent, basin geology. Griffiths (1982) considered that secondary climatic effects, such as differences in the intensity, frequency, and duration of storms, are also important.

The total volume of suspended sediment transported through the four sections on the Trotuș river between 2000 and 2014 amounted to approx. 39×10^6 t, thus the average annual volume was 2,598,000 t (Table 1). A large share of this suspended sediment yield was produced during major floods; for example, at Vrânceni ca. 61% of the total sediment yield for the 15 year- period under investigation resulted from just 3 flood events (2005, 2010 and 2012) (Fig.11).

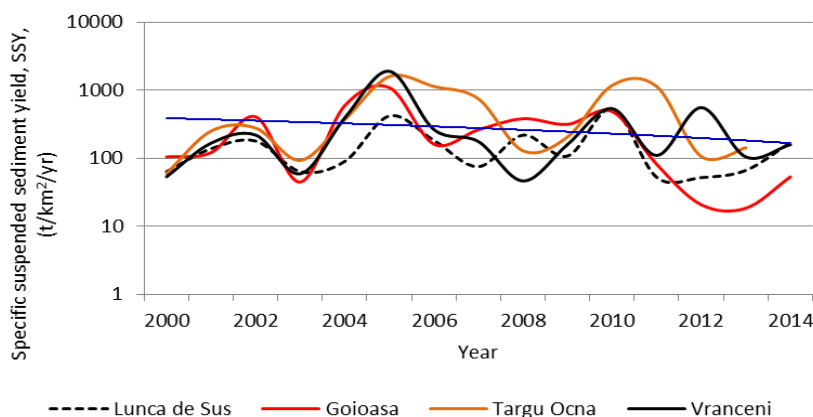


Fig. 11: Specific suspended sediment yield between 2000 and 2014 at the four gauging stations

It was found that at Târgu Ocna, the gauging station measuring the input of a drainage basin with an area of 2091 sqkm, the specific suspended sediment yield is 528.9 t/sqkm/yr, whereas at Vrânceni (which determines the input of a basin of 4092 sqkm) the specific suspended sediment yield is lower, i.e. 326.5 t/sqkm/yr, albeit the suspended sediment load is nearly double (37 kg/s compared to 19 kg/s) (Table 1; Fig.11). This can explain, to some extent, the tendency of aggradation of the Trotuș river bed/channel in the mid-course, and degradation in the lower course, but mostly the increase in colluvial or alluvial sediment storage (Vanmaercke et al., 2015). In fact, the inverse relationship between the specific suspended sediment yield and the area of the drainage basin was often reported in the literature (Schumm, 1977;

Dedkov, 2004; Dumitriu, 2014). This trend indicates that the total suspended sediment yield increases downstream, but to a lower extent compared to the increase of the drainage area. Thus, the specific suspended sediment yield diminishes as the drainage area augments. The highest suspended sediment yields were typically documented in wet years. This means that the climate might play an important role in the sediment transport process. There are, however, situations where, in certain dry years, spring floods contribute significantly to the increase of suspended sediment yield; this is the case of 2012 (with mean annual discharge far below the multiannual average - 22 m³/s compared to 34 m³/s), when 71% of the total sediment yield was produced in the course of one day (the 25th of May) (Fig.12).

Table 1 Data concerning the suspended sediment yield between 2000 and 2014 at the four gauging stations

Year	Lunca			Goioasa			Tg. Ocna			Vrânceni		
	SY	%	SSY	SY	%	SSY	SY	%	SSY	SY	%	SSY
2000	5597.0	2.6	63.6	81770.1	2.5	104.7	125109.2	0.8	59.8	218608.6	1.1	53.4
2001	12150.6	5.7	138.1	94455.2	2.9	120.9	524536.5	3.4	250.9	682379.0	3.4	166.8
2002	15737.9	7.4	178.8	317297.4	9.8	406.3	579367.2	3.7	277.1	895901.2	4.5	218.9
2003	5609.4	2.7	63.7	34884.1	1.1	44.7	194682.1	1.3	93.1	241448.3	1.2	59.0
2004	7906.6	3.7	89.8	463357.2	14.3	593.3	771868.3	5.0	369.1	1598895.2	8.0	390.7
2005	36739.0	17.4	417.5	852612.2	26.4	1091.7	3308048.3	21.4	1582.0	7769760.4	38.8	1898.8
2006	16131.7	7.6	183.3	125946.7	3.9	161.3	2372511.2	15.3	1134.6	1081169.5	5.4	264.2
2007	6620.6	3.1	75.2	205044.9	6.3	262.5	1559094.5	10.1	745.6	718561.9	3.6	175.6
2008	19204.0	9.1	218.2	296894.3	9.2	380.1	268380.0	1.7	128.4	189975.2	0.9	46.4
2009	9477.2	4.5	107.7	245545.8	7.6	314.4	429580.4	2.8	205.4	651620.1	3.3	159.2
2010	46466.3	22.0	528.0	378665.2	11.7	484.8	2457606.9	15.9	1175.3	2191510.7	10.9	535.6
2011	4616.3	2.2	52.5	63587.5	2.0	81.4	2372511.2	15.3	1134.6	450112.4	2.2	110.0
2012	4576.2	2.2	52.0	16196.7	0.5	20.7	221875.6	1.4	106.1	2274329.9	11.3	555.8
2013	5830.4	2.8	66.3	14371.2	0.4	18.4	299227.1	1.9	143.1	428297.8	2.1	104.7
2014	14976.7	7.1	170.2	41609.9	1.3	53.3				647567.5	3.2	158.3
Total	211639.9	100.0		3232238.5	100.0		15484398.4	100.0		20040137.5	100.0	
Av.	14109.3		160.3	215482.6		275.9	1106028.5		528.9	1336009.2		326.5

SY – suspended sediment yield (t); SSY – specific suspended sediment yield (t/km²/yr); % - period 2000 – 2014; Av. - average

Fig. 12: Mean suspended sediment yield a normal year, a wet year and a dry year

Conclusion

Concerning the monthly variability of suspended sediment load, after 1991 an over-concentration of sediment transport during the month of July was documented. At the four gauging stations, July accounts for the following percentages of the total amount of suspended sediment transported during the period under investigation: Lunca de Sus 33%; Goioasa, 37%; Târgu Ocna, 31% and Vrânceni 47%. During the summer season approx. 56% of the total suspended alluvia were transported. Regardless of the water year (wet, dry or normal average year) the catchment slopes are the primary source of suspended sediment. Even during dry years, river beds are unable to exceed 40-45% of

the total volume of suspended sediment transported by the Trotuș river. The sediment yield ranged from 4,576 t (Lunca de Sus – 2012) to 7,769,760 t (Vrânceni – 2005). The specific sediment yield is directly related to the area of the drainage basin in the mountain area (160 t/sqkm/yr at Lunca de Sus; 276 t/sqkm/yr at Goioasa and 529 t/sqkm/yr at Târgu Ocna), whereas in the Subcarpathians and plateau sectors the relation between the two parameters is inverse (326 t/sqkm/yr at Vrânceni).

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