Carpathian Journal of Earth and Environmental Sciences, November 2014, Vol. 9, No. 4, p. 31 - 46

SEDIMENT BUDGET OF THE ŞTIUCII LAKE CATCHMENT (TRANSYLVANIA PLAIN)

Nicolae RĂDOANE, Andrei ZAMOSTEANU & Maria RĂDOANE
"Stefan cel Mare" University of Suceava, Universitatii 13, 720229, Suceava, Romania, e-mail:radoane@usv.ro

Abstract: This paper showcases the sediment budget of a small catchment (i.e. 18.1 km^2) which supplies the water input for one of the oldest lakes occurring in the Transylvania Plain. The current sediment budget allows for the analysis of the present state of the sediment flux and will form the foundation for identifying the changes in the sediment dynamics throughout the Holocene in this region. The gross erosion of land has been estimated at 3453 t $km^{-2}yr^{-1}$, whereas the sediment yield was 216 t $km^{-2}yr^{-1}$. The sediment delivery for this type of catchment is 6.24%. Our results were analysed against the regional background as compared to similar results from Romania. The SDR curve for Ştiucii Lake catchment was discussed in relation to the size of the catchment and its drainage network order (Strahler's system).

Keywords: geomorphic mapping, sediment delivery ratio, drainage basin area, network order

1. INTRODUCTION

The Transylvanian Plain has always been a region of great attraction to geologists (Ciupagea et al., 1970) and especially to geomorphologists by its numerous palaeogeomorphological aspects (Savu, 1980; Pop, 2001), as well as the recent relief dynamics. As regards the latter angle, the large landslides (*glimee*) problem has long been one of the main trials for specialists in relief dynamics - Morariu & Gârbacea, 1968; Gârbacea, 1996; Mac, 1997; Surdeanu et al., 2011). Conversely, there has been a dimmer focus on the general denudational potential of the relief, capable of releasing and carrying sediments from the source area to the delivery area. Aside from some general approaches (Moţoc, 1983) or other singular aspects addressed in doctoral theses, as yet there is no detailed assessment of the contribution of various geomorphological processes to the sediment dynamics in the Transylvanian Plain.

Knowing the current state of the sediment system is of great importance to understanding the changes in its components throughout the Holocene in a region where palaeoclimate, palaeoecological (Feurdean et al., 2013) and palaeohydrological and river behavior (Perșoiu & Rădoane, 2011) reconstruction studies abound. Thus, the first stage of our study was focused on establishing the current parameters of the sediment system as resulted from mapping the sediment sources and storage, the relation with the dynamic of sediment-yielding geomorphological processes and the comparison with other areas in Romania.

The next stage of our research envisages analysing the temporal changes of the relationship between source-storage and sediment delivery by integrating the results obtained from borehole samples from floodplain deposits and absolute age dating of sediments horizons, supplemented by surface rezistivimeter measurements.

The concept behind the assessment of the sediment system in Ştiucii Lake catchment is the sediment budget approach described by Slaymacker et al., (2003) as an idea disarmingly simple in that it is an accounting of the sources, movements, and sinks of sediment in the landscape.

This concept was first introduced in Romania by Ichim (1986) and subsequently employed in various studies and punctual approaches (Ichim et al., 1998; Rădoane & Rădoane, 2005, Dumitriu, 2007). According to its established definition, the concept allows for a global and systemic approach of the sediment transfer phenomenon. Moreover, if the catchment is small-sized (as is the case with Bonţu stream supplying Ştiucii Lake), the chance of obtaining a more realistic sediment budget increases significantly (Dietrich & Dunne, 1978; Reid & Dunne, 2003). With all the critical aspects related to this concept (Parsons et al., 2006), interest in research in this area has increased. We take into account the practical implications, for example, watershed management with arrangements for hydropower lakes (Table 3), and numerous contributions on evolution in Holocene sediment budget parameters. Like Notebaert et al., (2009) we believe that SDR remains an important tool for understanding the sediment dynamics within a catchment, as it represents an essential part of the sediment budget which is closely connected with all the processes occurring in the sediment cycle (erosion, transport and deposition at different scales).

Considering this theoretical foundation and the motivation for the present study, the paper has the following structure: introducing the study area, as well as the work methods and techniques applied, the geomorphological map emphasizing the sediment-yielding processes, assessment of the sediment yield and the sediment delivery, preliminary discussions regarding the spatial distribution of the results and implications for future research.

2. STUDY AREA

Valea Bonțului catchment has an area of 46.2 km^2, and is a direct tributary of Fizeş River with whom it merges in the vicinity of Gherla urban area (Fig. 1). The catchment is known mainly due to the fact that it encompasses one of the typical lakes from the Transylvanian Plain in its upper sector, i.e. Știucii Lake. The primary focus of the sediment budget research is on the catchment sector located upstream of Știucii Lake (A = 18.1 km^2); however, in order to better understand the lithological, tectonical and paleoevolution context of the area, we will refer to the entire catchment of Bonțu River.

The geological composition of the substrate comprises predominantly of soft sedimentary rocks, i.e. marls, marlyshales, clay, tuff, sands and gravel. Their ages range from Badenian (in the lower catchment) to Volhinian-Bessarabian (in the highest sectors), whereas Quaternary deposits occur in the valley bottoms.

As regards the process of relief shaping to its current state, it was initiated subsequent to the withdrawal of lacustrine waters from the Transylvanian Depression during the Pliocene. In the first stage, the emerging relief resembled a slightly wavy plain due in part to the disturbances created by the tectonics of salt deposits. Undoubtedly, this plain relief was also slightly sloping to the North, towards the current Someş river corridor, also known as „The Someş Gate" (Paucă, 1977). By this corridor the waters from the northern sector of the palaeolake withdrew. In this area, the first streams to set in were the two Someş rivers, both of which converge to the couloir they have taken over. Their junction in Dej is not random, as both Someşu Mare and Someşu Mic have settled onto marginal faults, and Dej area has been subject to a local sinking process due to the occurrence of a fault system consisting of several faults moving at differents rates (Ciupagea et al., 1970). The valleys have rapidly deepened, and the process was accelerated by the lifting processes subsequent to the Late Pliocene - Early Quaternary. Therefore, Bonțu catchment is arguably the third generation of Romanian - Quaternary valleys.

In this Davisian approach of relief evolution, the 76% hypsometric integral (Fig. 2C) provides the mass size of the relief dislocated from the initial Pliocene - Pleistocene surface. Thus, we can infer the youth of this relief and, consequently, the high potential for sediment delivery.

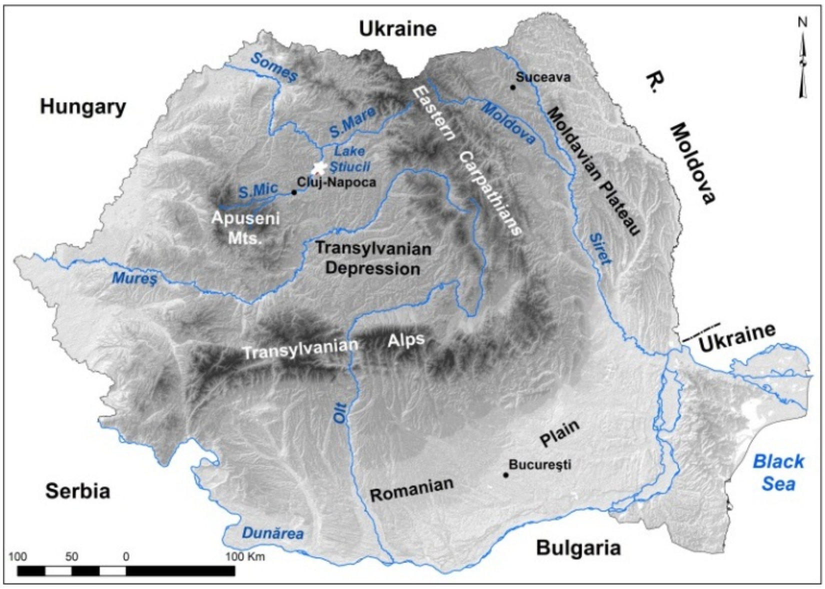

Figure 1. Position of study area.

As regards the land use/land cover, pastures take up almost half of the catchment area (44.5%), followed by strips of agricultural land separated by natural vegetation (32.4%) and deciduous forests (13.2%). Also peculiar to this area are the thick rush-beds occupying valley beds (2.1%), where numerous species of birds nestle. In 2000 the rush-beds from this area of the Transylvanian Plain were declared a National Nature Reserve (cf. Law No.5-March 6, 2000).

3. WORK METHODS

Geomorphological mapping was the main method for assessing the sediment sources and, in general, the morphodynamic potential of the study area. This approach resulted in a geomorphological map (Fig. 4), designed according to the Morphometry-Genesis-Age principle (Klimaszewski, 1990). The geodatabase contains spatial data on morphometry/ morphography, river network, genesis and age of landforms and geomorphological processes. Some of the data required field identification (e.g., the extension and height of hillslope terracettes, the main scarps, the typology of current processes), whereas others were derived from digital terrain models, 1:5000 topographic survey maps or the literature (such as the age of landforms). The analysis and graphical processing of geomorphological features were performed using the ArcView 9.2 software, after the necessary symbols were generated according to the established legend.

In order to assess the sediment budget we employed the classical model introduced by Dietrich & Dunne (1978), which requires detailed mapping of all the areas undergoing specific processes (erosion or accumulation) and an estimate of their activity rates.

The evolution rates of geomorphological processes were determined by means of interpolation of measurement results from research areas with similar physiographic conditions to the Transylvanian Plain.

4. THE MORPHOMETRIC SETTING OF THE STUDY AREA

Morphometric measurements were performed on the entire Bonţu drainage basin (of which we subsequently selected the sector upstream of Ştiucii Lake) in order to get a better understanding of the spatial context of our investigations.

Morphometric data are the first quantitative metrics to describe a geomorphological fluvial system. From the array of variables introduced by both hydrologists and geomorphologists over time (Strahler, 1957; Chorley et al., 1984; Goudie, 1990) we selected those listed in Table 1. The acquired data were generated based on the 3D model we produced by employing the information provided by the 1:25000 scale topographic map, ed. 1983, and orthophotos of the area, ed. 2005.

Of the relief features bearing an overt significance to the morphodynamics of the territory we singled out the hypsometry and the slope gradients, which were subjected to a distinct analysis.

The relief of Bonţu catchment spans over an elevation range of 332 m, which is rather characteristic for most small catchments from this area of the Transylvanian Plain (Fig. 2A). The shape of the elevation histogram (Fig. 2 B) shows a slight tendency towards bimodality, whereby the secondary mode is centered on the 240 m elevation. The primary mode, which is the dominant one, is centered on the 320 m elevation and delineates the hillslope domain within Bonţu catchment.

The second mode (i.e. the 240 m) is assigned to the valley floors within the catchment, which leads to our first observation noting that in the drainage basins pertaining to the Transylvanian Plain, the floodplain domain becomes significant early on, in the low order (2^{nd} and 3^{rd}) drainage network. On the other hand, the hypsometric integral has a convex shape, which reveals the young age of the landforms (as expected), compared to the evolution of this geographical area.

Table 1. Morphometric parameters of Bonţu river catchment

Morphometric variable	Bonţu catchment (entire)	Bonţu catchment upstream of Ştiucii Lake	Ştiucii Lake
Perimeter, *P*, km	39.4	18.65	2.711
Area, *A*, km^2	46.26	18.14	0.5735*
Maximum elevation, *Hmax*, m	562	521	
Minimum elevation, *Hmin*, m	232	265	
Average elevation, *Hmed*, m	350	359	
Maximum energy, *Emax*, m	332	256	
Average slope gradient, *Ib*, %	15	10	

*cf Serban & Sorocovschi (2003)

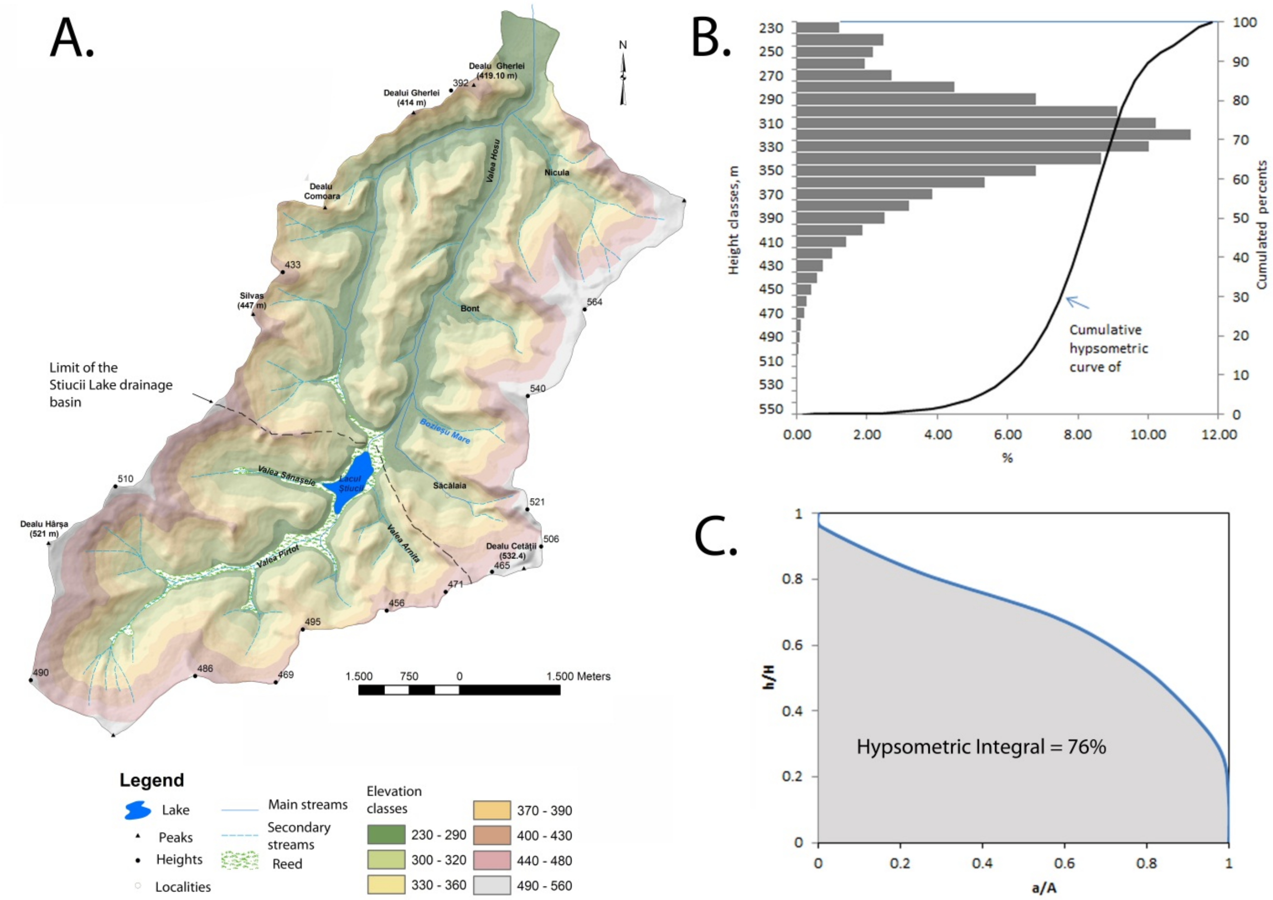

Figure 2. A. Hypsometric map of the Bonţu drainage basin. B. Hypsometric curves of the Bonţu drainage basin. C. Integral hypsometric.

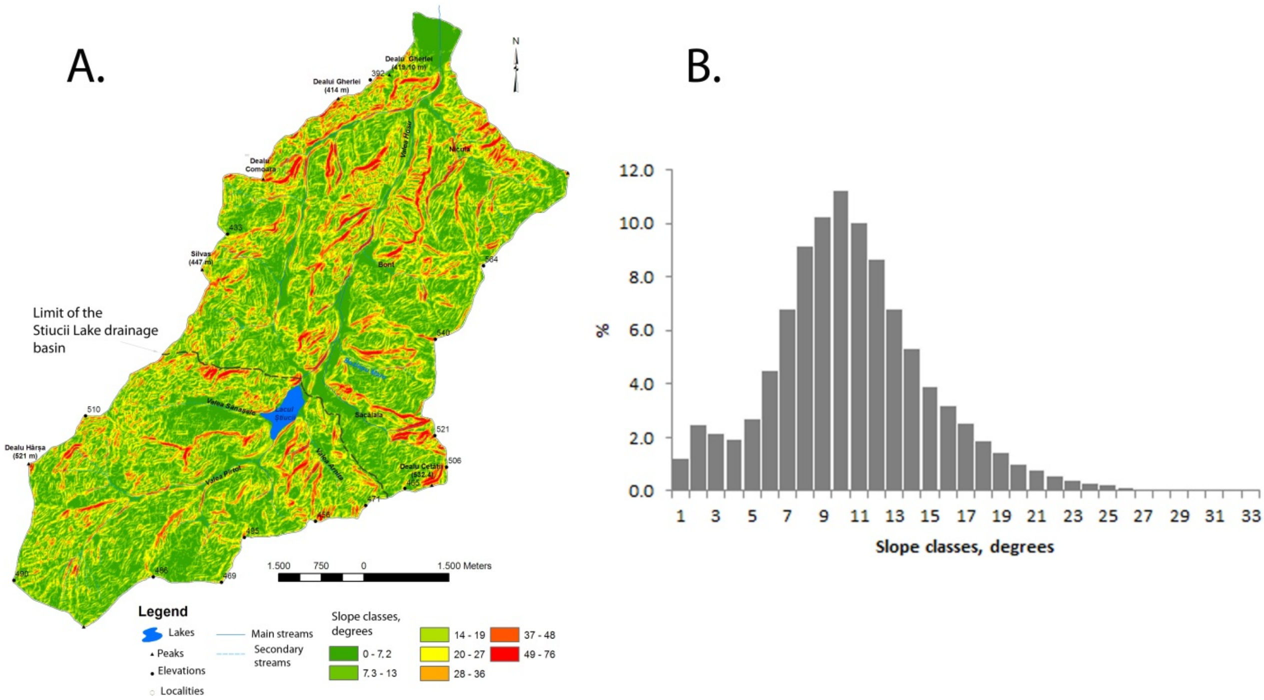

Figure 3. Slope distribution in the Bonţu drainage basin. A. Areal distribution. B. Slope histogram.

However, as will be shown by the sediment budget equation, the geomorphological effectiveness of these rivers is very limited.As regards the slope gradient distribution within the catchment (Fig. 3), the dominant modal is 10 degrees (for the hillslope domain), whereas the second distinguishable mode (under 2 degrees) delineates the valley floors (Fig. 3B).

The steep top escarpments rank highest in terms of the slope gradients (above 25 degrees), whereas towards the bottom of the scarp hillslopes the slope gradients decrease to approx. 17 degrees (within the landslide main body), or 10 degrees (in deluvial and mixed-type glacises) (Fig. 4).

Figure 4. Geomorphological map of Bonţu river catchment, tributary of Fizeş River.

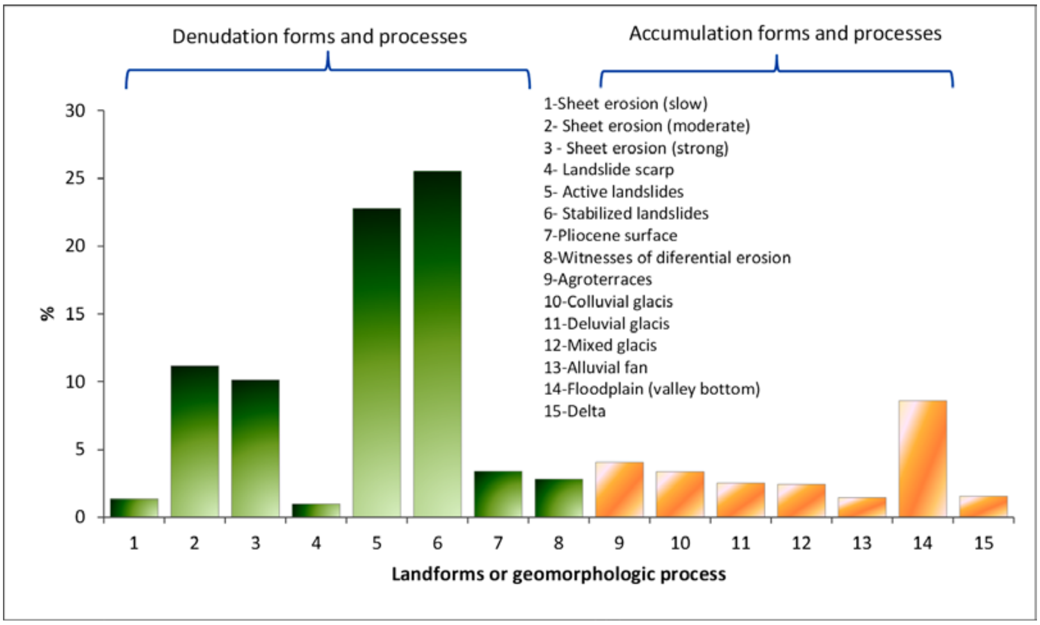

Figure 5. Percentage weight of the various types of landforms and geomorphological processes in Ştiucii Lake catchment.

5. THE GEOMORPHOLOGICAL MAP

5.1. Distribution of relief types

Before proceeding to perform an analysis of the current landform shaping processes and assessing the sediment budget in Bonţu river catchment, it is requisite to provide a summary of the main types and forms of relief within the study area. The geomorphological map (Fig. 4) indicates the prevalence of three types of relief, with their specific forms, i.e. structural relief, fluvial - denudational relief (covering the largest portion of the catchment, often overlapping the structural relief) and fluvial relief. While other types of landforms occur in the study area, their presence is limited and they are not very apparent (as is the case with lacustrine relief and even anthropogenic relief).

The **structural relief** is the class of landforms whereby salt tectonics has played a prominent role through the two structural lines mentioned before: the Cojocna-Sic-Dej anticline crossing under the middle section of Stiucii Lake, and the syncline following almost entirely the (interfluvial) watershed separating Somesu Mare and Bonţu river basins. Both have resulted in distinct relief features, such as structural surfaces, i.e. cuestas, whose formation was also favoured by the presence of tuff strata and thin sandstone layers. Cuestas are linear, spread along the right flank of river valleys.

The **fluvial - denudational** landforms cover the largest portion of the catchment. In addition to the sculptural forms we mentioned previously, i.e. the erosion surfaces, selective erosion features are also present in this area (witnesses of differential erosion and saddles). Other common landforms include relief features created by landsliding and/or water-generated erosion, particularly gully erosion. Other erosion-derived landforms are the ones created by accumulation of displaced sediments (alluvial fans,colluvial glacis).

Fluvial landforms are mostly represented by river channels and floodplains (Bonţu Valley downstream of Ştiucii Lake, Sarata Valley, as well as valleys of several tributaries of Bonţu River downstream of the lake). In general, these are small-sized channels which allow for the water discharge, particularly during flood events. Upstream of the lake, the tributaries lack proper channel to a large extent; one of the streams illustrating very well this tendency is Pârtoț stream, which lacks a channel on most of its length, due to sediment accumulation („clogging”). Among the **anthropogenic landforms** stand out the features created by direct human intervention, such as rectification of river channels and channeling (Bonţu river channel, and Sacalaia and Nicula streams). This category of relief can also include roads perpendicular to contour lines, whose traces have often turned to gullies, as well as man-made terracettes on hillslopes, particularly in the sector upstream of the lake, many of which were eventually destroyed by landsliding.

5.2. Assessment of sediment sources and storage

The assessment was performed for the catchment sector upstream of Ştiucii Lake; this was the area of greatest relevance to the investigations on the paleoenvironmental archive in this area of the Transylvanian Plain, and will be our focus area throughout the next stages of our research.In order to evaluate the parameters of the sediment budget we separated the two main categories of geomorphological forms and processes, i.e. erosion and accumulation.

Erosion processes and derived landforms (either natural or anthropogenic) result in the dislocation and displacement of sediments, whereas accumulation landforms serve as residency area for the sediments which have not been discharged to Ştiucii Lake yet.

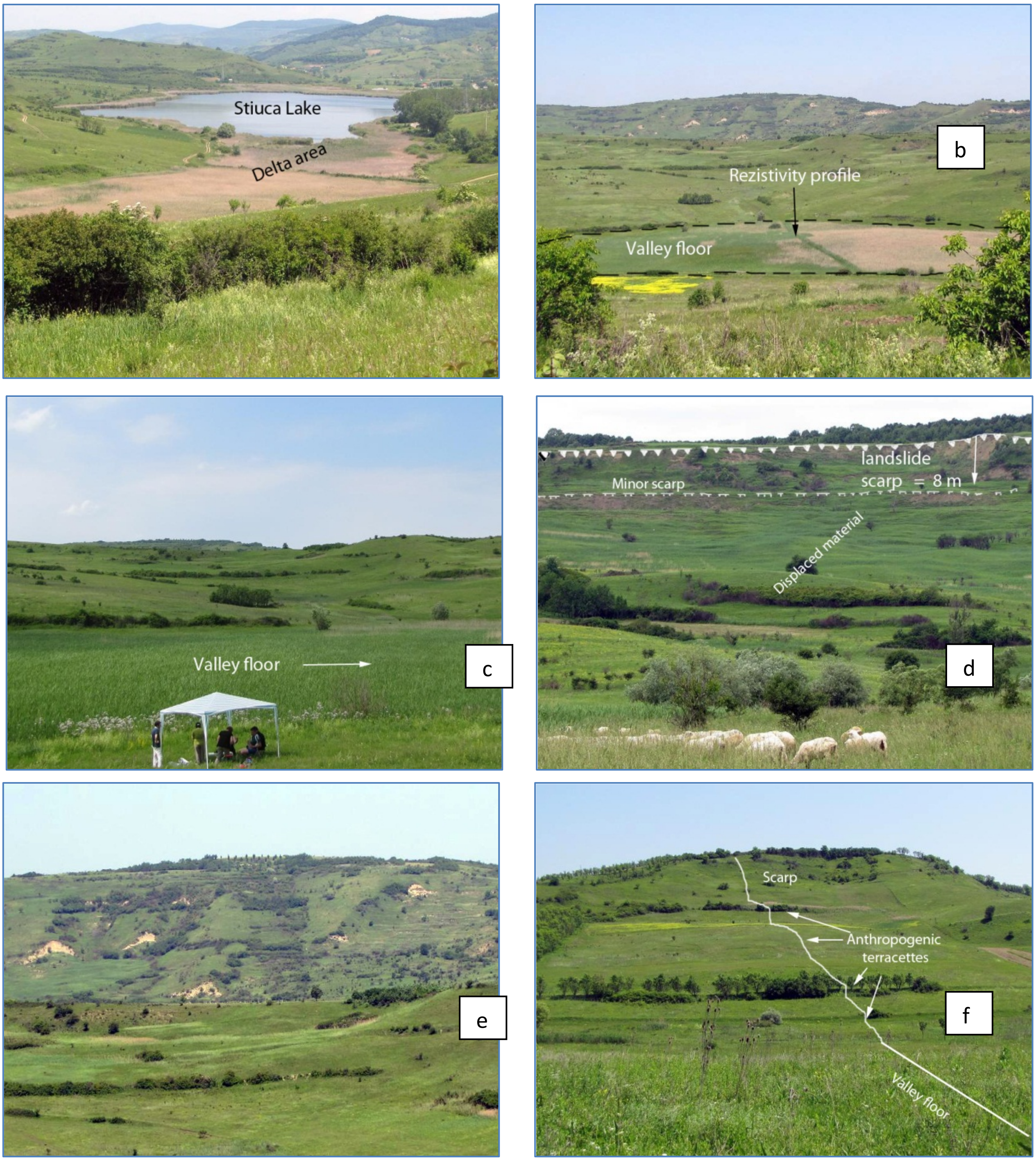

Figure 6. Illustrating current geomorphological processes in Ştiucii Lake catchment: a) Ştiucii Lake and view on the present-day deltaic area, covered with reed; b) general view on the erosion-dominated (sediment source) and accumulation-dominated (sediment storage) areas. The current floodplain of Bonţu stream is oversized as it was originally the basin of Ştiucii Lake; c) zonation of Bonţu river upper catchment based on landform genesis; d) sequence of main scarps, landslide main body and contact with the current valley bottom; e) polymorphous erosion on the hillslope of Bonţu river; f) relief vestiges of anthropogenic terracettes (foto N. Rădoane).

Each process is characteristic for a certain section of the catchment under analysis; based on this assumption we generated a diagram (Fig. 5) whereby we identified the contribution (in terms of area) of each type of geomorphological process to the sediment budget. Note that within the same area several geomorphological processes can occur simultaneously. Below we present a set of suggestive images displaying our geomorphological mapping approach, i.e. identifying the types of processes and the scale of erosion and accumulation phenomena (Fig. 6).

Within the 18.1 km^2 area of the upper Ştiucii Lake catchment we found 8 categories of erosion landforms and processes and 7 categories of accumulation forms and processes. In the following sections each relevant category will be discussed separately and the amount of displaced/accumulated sediment will be assessed.

5.2.1. Erosion processes

Sheet erosion affects 78% of Bonţu stream catchment area (upstream of Ştiucii Lake), of which 27% undergoes the most aggressive manifestation of these processes. In this case, the contribution of sheet erosion is the most consequential as its product becomes suspended sediment which is eventually discharged to Ştiucii Lake basin to a great extent. This process affects all sloping surfaces, the most intensely eroded of which are terrains with slope gradients ranging from 7 to 14 degrees (i.e. 51% of the investigated area). However, the effects of sheet erosion in terms of sediment release depend on several other factors (integrated in the famous USLE equation by Wischmeier & Smith, 1965), as well. In our case, land use (i.e. 69% of catchment area covered by pasture, shrubbery and forest) can limit the erosion rate. The only bare terrains (undergoing the greatest exposure to sheeterosion) in Bonţu river upper catchment are landslide main scarps (Fig. 6 e) with slope gradients above 30 degrees, which easily release sediments. Overall, their contribution is rather low due to their small share of just 1% of the study area. Moreover, agricultural terrains (in the shape of strips with inserts of natural vegetation) have high efficiency in terms of the sediment input during their so-called „dead-fallow" stages (Moţoc, 1983).

In order to assess the sediment input of each type of process to sediment mobilization we used as a guide the measurements conducted on plots from various regions in Romania (Table 2) with similar conditions to the Transylvanian Plain in terms of the climate, runoff and soil types (Moţoc, 1983; Popa et al., 1984; 2013; Ioniţă et al., 2006). Thus, the lowest erosion rate was measured on the Bromus plot (perennial grass similar to grasslands in terms of erosion control efficiency), whereas the highest rate was documented in bare land plots (dead-fallow).

Therefore, based on the detailed mapping of the types of sheet erosion processes, correlated with land use, slope gradient and hillslope area, we were able to assess that sheet erosion (low, moderate and high) in the catchment upstream of Ştiucii Lake accounts for cu 568 tkm^{-2} yr^{-1} of the gross erosion.

Table 2. Centralized data on erosion rates by measuring plots

Location	Measuring period	Plot land use	Slope gradient %	Erosion rate t $ha^{-1}yr^{-1}$	Source
Perieni, Vaslui	1995-2012	Bromus		0.12	Popa et al., (2013)
		Wheat		0.79	
		Beans		5.40	
		Corn		8.93	
		Dead-fallow		42.37	
PoduIloaei, Iasi	1965-77	Wheat	16	2.7	Ioniţă et al., (2006)
		Corn		17.2	
		Sunflower		20.8	
Aldeni, Buzau	1975-81	Wheat	18	7.0	
		Corn		26.6	
		Dead-fallow		44.8	
Bilcesti, Arges	1968-85	Orchard on hillslope without terraces	25	5.10	
		Orchard on hillslope with terraces		2.80	
CeanTurda, Cluj	1950-59	Wheat	7	0.67	
		Corn		7.90	
		Winter wheat	12	0.90	
		Corn		12.4	

Landslides (both active and stabilized) affect 49% of the study area. The slope gradients which are characteristic for landsliding range from 14 to 30 degrees. Most of the main body material (i.e. displaced from the upper half of the hillslopes) is not discharged into the stream network, and instead is stored by the slope foot (mostly, in the shape of deluvial glacises). Therefore, only the toe (front) of the landslide body which comes in direct contact with the river channels represents a direct input to the sediment budget. The remaining material from the landslide body is prepared to supply a further displacement when favourable conditions for sediment transport will arise.

Knowing the area covered by active and stablized landslides and the height of the main scarps, we were able to assess the thickness of displaced sediments. As regards the denudation rate by means of landsliding, we used as a reference the measurements performed by Pujină (2008) over the duration of 21 years in the Moldavian Plateau, whereby external conditions are similar to the Transylvanian Plain in terms of the lithology, slope gradients and climate aggressivenes. Thus, we estimated that the displacement rate by landlisding is roughly 2745 t $km^{-2}yr^{-1}$. Measurements by Pujină (2008) show that just 2% of the displaced amount of sediments are eventually discharged in the 2nd, 3rd and 4th order drainage network (Strahler's system) (due to the phenomenon known as coupling between the hillslope and the channel according to Fryirs & Brierley (1999), and its role in sediment delivery). In our case, the hillslope-channel coupling accounts less than 2% due to the drainage network „clogging", which will be discussed further.

Other sediment-generating landforms and processes are ravines and gullies, field paths and channeled streams. In order to assess their inputs we took into account the measurement results obtained by Rădoane et al., (1999); Ioniţă (2000); Rădoane N. (2002). Rills and gullies, field paths and channeled streams account for under 1% of the study area, and their contribution to sediment displacement was evaluated at approx. 150 t km^{-2} yr^{-1}.

5.2.2. Accumulation processes

The accumulation sites for sediments eroded from the hillslope catchment are found commonly within the colluvium, alluvial fans, floodplains and the deltaic area pertaining to Ştiucii Lake. The slope gradients characteristic to accumulation sites range from 1 degree on the valley bottom to 5-7 degrees in glacises. The diagram in figure 5 shows that all these forms of sediment storage amount to 24% of the catchment upstream of Ştiucii Lake.

Among the areas which act as sediment storage within Bonţu stream catchment, its floodplain holds by far the largest share in terms of area. The bottom of the valley is clearly oversized as compared to the actual shaping capacity of this stream. At present this broad floodplain, which is highly humid, is not used for agricultural purposes and is covered entirely by rush-beds. In the current stage of our research we have not performed an assessment of the amount of stored sediments, as our borehole samples have yet to be fully processed. However, all the results we obtained so far indicate a high susceptibility of river valleys to becoming „clogged" by sediments, a phenomenon somewhat similar to the „premature aging of the drainage network" occuring in the southern Moldavian Plateau (Filipescu, 1950).

6. ASSESSMENT OF THE SEDIMENT YIELD AND SEDIMENT DELIVERY

The equation we used was introduced by Roehl (1962) as the relationship between the *specific sediment yield* (Q_s, t km^{-2} yr^{-1}) accounting for the sediments evacuated from a catchment through a closing section (in our case, Ştiucii Lake) and the *gross erosion rate* (E_v, t km^{-2} yr^{-1}), i.e. the resultof the combined action of all geomorphological processes on the geological substrate (bedrock, hillslope deposits, soil) in the upstream catchment:

$$SDR = \frac{Qs\,(t\ km^{-2}yr^{-1})}{Ev\,(t\ km^{-2}yr^{-1})} \cdot 100 \qquad (1)$$

where the *SDR* (%) stands for the sediment delivery ratio. In this form, the relationship is very logical; however, applying it to absolute data is the true difficulty in solving this equation (Wolman, 1977); from the gross erosion of the hillslopes in the catchment to the sediment yield there is a cascade of sediments for which Walling (1983) used the term "black box". Shedding some light on this black box is the real challenge for most researchers; some believe that this is actually the secret behind this "disarmingly simple" (Slaymacker et al., 2003) concept, albeit with such broad applicability, in many fields. In section 5.2 we attempted to bring our contribution to empirically deciphering of a sediment budget. In the following section we will try to solve eq (1) by approaching each parameter.

6.1. The specific sediment yield, Qs

The catchment of Bonţu stream has never been systematically monitored in terms of the water discharge and sediment load, such that our assessment of the specific sediment yield was made:

- indirectly, by interpolating data on the specific sediment yield measured nationwide;
- based on the sediment storage capacity provided by Ştiucii Lake (Şerban & Sorocovschi, 2003).
- based on absolute dating of sediments in Ştiucii Lake (Feurdean et al., 2013).

In the first case:

Based on the dataset comprising 336 drainage basins across Romania, located in various morpho-lithological conditions (Rădoane & Rădoane, 2005, updated), whereby we integrated measurements made in catchments from the Transylvanian Plain (Sorocovschi et al., 1992), we estimated that the specific sediment yield of Bonţu catchment upstream of Ştiucii Lake ($A = 18.1\ km^2$) amounts to $280\ t\ km^{-2}\ yr^{-1}$. The position of the catchment in the diagram shown in figure 7 indicates that Bonţu stream is very close to the national average in terms of the specific sediment yield. Also, it is located among relatively similar morpho-lithological regions (such as the Moldavian Plateau, the Moldavian Plain or the high Plain of Oltenia), all of which comprise of highly erodible lands, albeit the slope gradients are too low for the geomorphological work to be efficient.

In the second case:

According to Şerban & Sorocovschi (2003), between 1957 and 2000, over 1.84 mil m^3 of sediments were stored in Ştiucii Lake. The volumetric weight of the sediments was estimated at $1.57\ g\ cm^{-3}$, considering the particle size composition and the degree of compaction of the sediments (based on the measurements performed on sediments from Izvoru Muntelui Reservoir - Rădoane, 2004). Calculations yielded

$$((1\,840\,000\ m^3 yr^{-1} \times 1.57\ g\ cm^{-3}):18.1\ km^2):43\ yr = 3711\ t\ km^{-2} yr^{-1} \quad (2)$$

resulting in a rather puzzling specific sediment yield in Bonţu catchment.

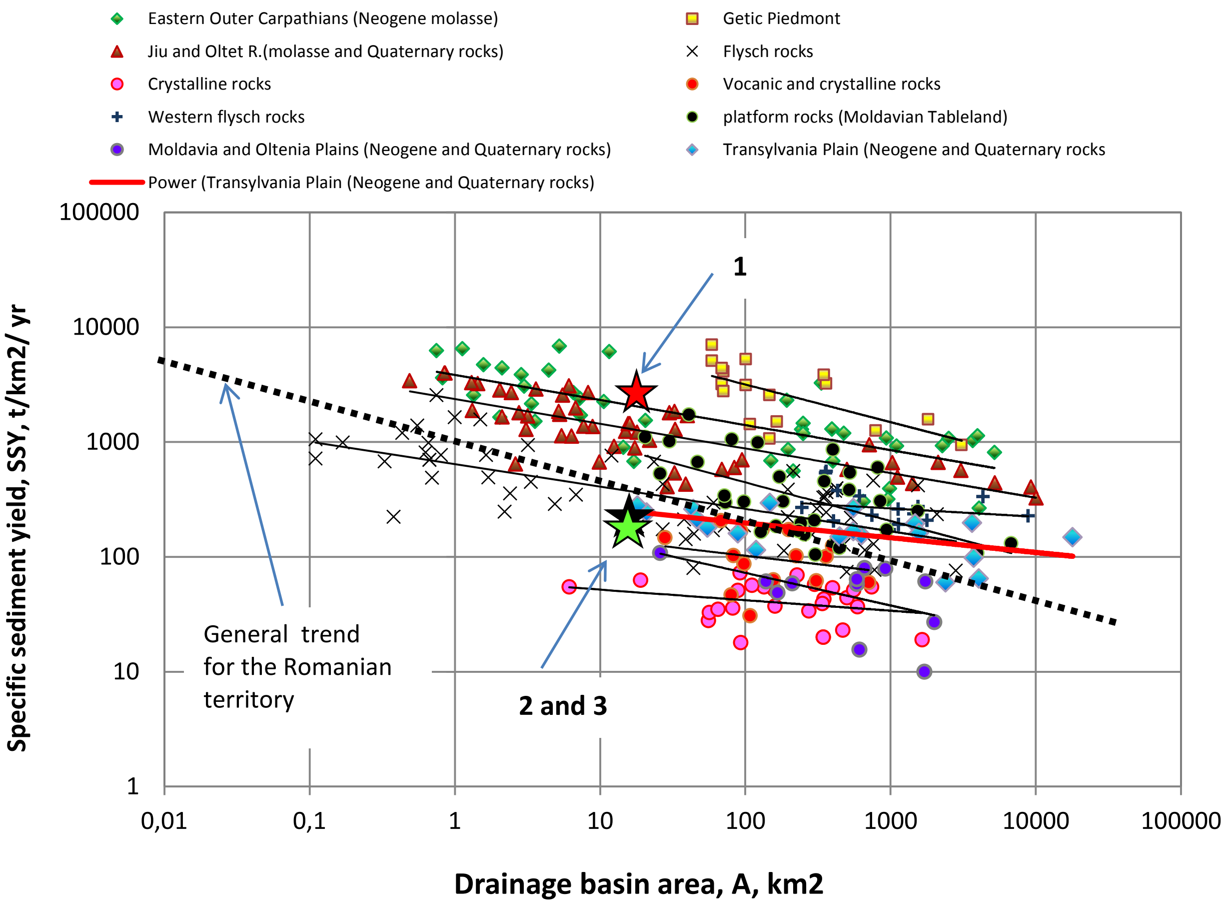

Figure 7. The rank of Bonţu stream in terms ofthe specific sediment yield against the regional background (estimated based on the suspended sediment load of rivers by Rădoane & Rădoane (2005, updated)) indicates the study area ranges between 250 and 500 $t\ km^{-2}\ yr^{-1}$ (2 - black star), very close to the value averaged for the Romanian territory. The specific sediment yield estimate using the sedimentation rate in the Ştiucii Lake (Feurdean et al., 2013)(3-green star). The specific sediment yield amounting to 3711 $t\ km^{-2}\ yr^{-1}$assessed based on the sediment storage in Ştiucii Lake (according to Şerban & Sorocovschi, 2003) is indicated by 1 - red star.

The obtained value, i.e. 3711 t km^{-2} yr^{-1}would indicate that this catchment ranks very high in terms of thesediment delivery potential values, similar to those calculated for catchments located in the Neogene molasses or the Getic Piedmont (Fig. 7), whereas, in fact, the potential of Bonţu catchment is far from these regions.

The problem with the outcome of equation (2) derives from the young age of lake sediments, i.e. just 43 years. If the sedimentation rate had remained constant throughout the history of Ştiucii Lake, the life expectancy of the lake would not have exceeded 100 years. However, Sandulache & Buta (1963) refer to the Medieval Period of the lake, whereas Mac et al., (1987), albeit not mentioning the source, showed that pollen analyses performed on floodplain deposits from several river valleys from the Transylvanian Plain, including Fizes valley indicate the formation of the lakes under a cool post glacial climate. Moreover, Feurdean et al., (2013) produced evidence that the age of the bottom of the 4 m sediment core extracted from Ştiucii Lake is 4000 years. Therefore, it appears that the 1.83 mil m^3(and surely, more than this amount) of sediments are likely at least 4k old. However, in this stage of our research we are unable to produce a reliable value for the sediment storage in Ştiucii Lake and the adjacent areas until borehole sample analyses and surface rezistivimeter measurements are completed.

In the third case:

The latest research conducted by Feurdean et al., (2013) brings to light new data regarding the accurate age of the lake, i.e. 4700 years, throughout which it has undergone significant level changes. The thickness of the accumulated sediments and their absolute dating have allowed for calculation of the sedimentation rate, which amounted to approx. 1 cm of sediments per every 20 years during the past 3500 years. Thus, considering an annual rate of 0.05 cm yr^{-1}, the maximumamount of sediments deposited annually in Ştiucii Lake would be about 2500 m^3 yr^{-1} or 3925 t yr^{-1}. This value divided by the source area yields:

$$3925 \text{ t yr}^{-1} : 18.1 \text{ km}^2 = 216.8 \text{ t km}^{-2} \text{ yr}^{-1}$$

Note that the specific sediment yield computed based on the sedimentation rate over a long time frame is very similar to the value resulted from the suspended sediment load measurements conducted in the Transylvanian Plain region.

To conclude, for further calculations of the present day sediment budget, we will take into account the 216 t km^{-2} yr^{-1}value for the specific sediment yield (Fig. 8), as we believe it is the closest to the actual situation in the study area.

6.2. The gross erosion, Ev

By summing up the contribution of all denudational geomorphological processes (as assessed in chapter 5.1):

$$568 \text{ t km}^{-2} \text{ yr}^{-1}\text{(sheet erosion)} + 2745 \text{ t km}^{-2} \text{ yr}^{-1} \text{(landslides)} + 150 \text{ t km}^{-2} \text{ yr}^{-1}\text{(other processes)}$$

we determined that they displace an overall amount of sediments of 3463 t km^{-2} yr^{-1} (Fig. 8). According to estimates made by Moţoc (1983), the area of Bonţu catchment ranges from 1500 t km^{-2} yr^{-1}. However, our assessment is more accurate than the results obtained by Motoc, as our study area was considerably smaller and was thus mapped and assessed in great detail.

6.3. The sediment delivery ratio, SDR

In order to determine the sediment delivery ratio (SDR), we used the values obtained in chapters 5.1. and 5.2. in eq. (1)

$$SDR = (216/ 3463) \times 100 = 6.24\% \quad \ldots\ldots\ldots\ldots\ldots.. (3)$$

The result shows, in terms of percent values, how much of the amount of rock displaced within a catchment is ultimately evacuated from it. In our case, these are fine to very fine sediments which reach Ştiucii Lake.

The low value of SDR, i.e. just 6.24 %, indicates the poor efficiency of transport processes within Bonţu stream catchment (Fig. 8), albeit geomorphological processes are commonly able to displace large amounts of materials from the hillslopes. The majority of these sediments are deposed before being discharged into Ştiucii Lake basin, thus explaining the large lifespan of the lake, which now hosts an impressive paleoenvironmental archive (Feurdean et al., 2013).

7. DISCUSSIONS AND CONCLUSIONS

The results we obtained in this small area pertaining to the Transylvanian Plain regarding the present day sediment budget are only significant if considered in a regional context. Thus, we compared them to results yielded by other studies from Romania, particularly from the Eastern part, such as the Moldavian Plateau, the Moldavian SubCarpathians, the Eastern Carpathians, as well as the Getic SubCarpathians and the Getic Piedmont. There are several factors influencing the sediment delivery ratio and their interactions are extremely complex (Walling, 1983; Richards, 2002), therefore the empirical method is used for SDR regionalization.

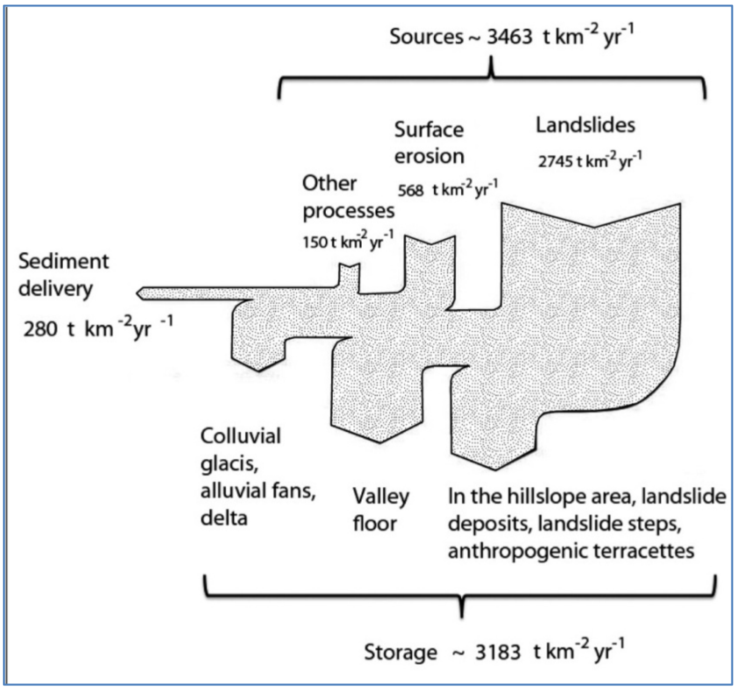

Figure 8. The sediment budget of Bonţu stream catchment, outflow of Ştiucii Lake.

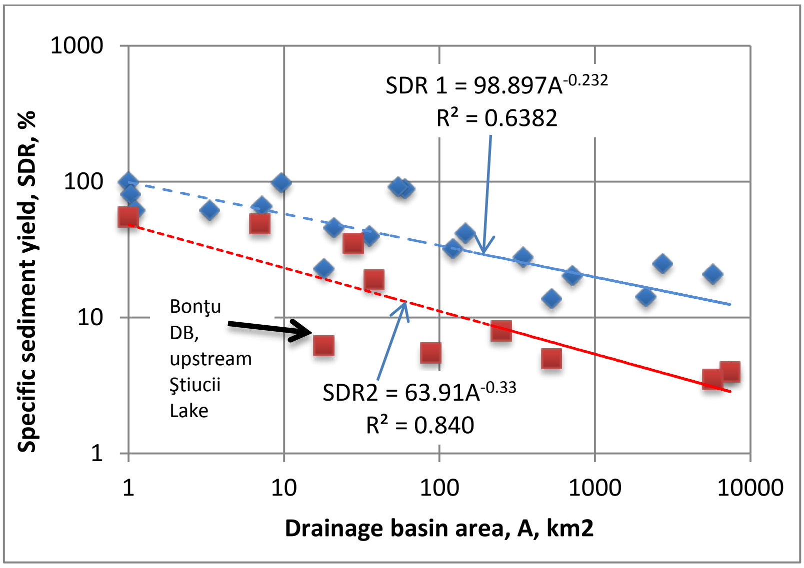

Figure 9. The sediment delivery ratio curve as a function of the catchment size in the Carpathian and SubCarpathian area (SDR1) as compared to the plateau and higher plain areas (SDR 2) in Romania.

One of the most established relations is the one between SDR and the catchment area as power function (Fig. 9). SDR may range from 0 to 1 or 0 to 100%, but the correlation slope between SDR and the catchment area differs according to the location of the catchment on the Globe. Its values may range from -0.01 to -0.7 (according to Walling, 1983, Ferro & Minacapilli, 1995; Lu et al., 2006).

We selected and synthesized a number of results obtained thus far for the Romanian territory (Rădoane & Ichim, 1987; Rădoane & Rădoane, 2001), which are shown in Figure 9. The diagram indicates that SDR varies greatly even within areas smaller than the national territory: a smaller variation slope (-0.21) for Carpathian and SubCarpathian catchments (SDR1) and a greater slope (-0.33) for the plateau and higher plain catchments (SDR2). This phenomenon is linked to the energetic potential and the sediment evacuation capacity. If up to A ~ 10 km^2, the correlation curves have very similar slope gradients, as the catchment area increases, the rhythm of the variation changes noticeably. In catchments located in the plateau and higher plain areas SDR drops under 5%, whereas in the Carpathian and SubCarpathian areas the evacuation of sediments in catchments over 2000

km^2constantly ranges above 20%.

The evacuation of sediments from a drainage system is dependent not only on the capacity of the outflow, but also on the organisation of the drainage network (Richards, 2002). Our empirical approach of the results included an exploration of the effects of the drainage network order (Strahler's system) (Rădoane & Ichim, 1987). Considering the emphasis on the drainage network, an important role is played by the slope-channel coupling phenomenon in sediment displacement and evacuation.

By using a vastly enhanced database with new entries (Table 3) we re-computed the relation between SDR and the drainage network order in the same regional context across Romania. Thus, we can better understand the rank of our study area as regards the sediments dynamics.

By plotting the data (Fig. 10) we were able to find subtle differences as regards the changes in the SDR throughout a given area. In drainage networks whose order (Strahler's system) is below VII, the variability of SDR is described by sinusoidal bends, either concave or flared. We also placed on the diagram the SDR curve of Bonţu basin (nr. 10, Fig. 10) in order to compare the results for a typical area from the Transylvanian Plain to other regions in Romania.

The shape of the SDR curves is strongly related to the landform hosting the catchment. Moreover, catchments from the higher plains and plateaus rank among a very sinuous group of curves, whose shape is generated by the rapid decline in the sediment load from 2nd to 3rd order elements of the drainage system. Conversely, all other catchments from the SubCarpathian and piedmont areas rank among the flared-type curves, due to the fact that the sediment load remains significant in the higher order drainage network. In the mountain area the SDR curve is largely concave whereby the inflexion point occurs in the lower order drainage network and the curve becomes asymptotic in the higher order network.

Bonţu stream catchment displays features which are very similar to the catchments located in the Moldavian Plateau, i.e. high efficiency of sediment yield in the 1st and 2nd order drainage network ensued by a steep decline following the 3rd order. The sediments are retainedat the base of the hillslopes, and especially on the valley floors, resulting in broad, wet valleys covered in rush-beds (in the Transylvanian Plain), drained by feeble rivers carrying low sediment loads.

In the mountain catchments the SDR curves have higher concavity in 1st, 2nd, 3rd and 4th order networks, after which the variation slope ranges around 20%. Although the transport capacity of the drainage network is high, due to the relatively low amount of sediments, the balance is maintained between the sediment supply and evacuation.

The largest amount of sediments displaced by the drainage network occurs in the SubCarpathian and piedmont catchments (the connectivity to sediment sources is maximal); however, the evacuation of sediments is also high, reaching almost 50% in the 6th and 7th order network. The SDR curves are elongated and irregular, with large variations depending on the drainage network order.

Table 3. The sediment delivery ratio (%) related to the drainage network order (Strahler's system) in several key areas in Romania

Region	Drainage network order (Strahler's system)							Source
	I	II	III	IV	V	VI	VII	
Catchments in the flysch mountains	100.0	65.2	42.2	33.2	26.1	20.0	-	Rădoane & Ichim(1987), Rădoane (2002), Dumitriu (2007)
Catchments in the Eastern Sucarpathians and Curvature Sucarpathians(Neogene molasses rocks)	-	100.0	80.9	61.6	45.6	30.0	25.0	Rădoane & Ichim(1987), Rădoane et al (1997), Rădoane N. (2002), Dumitriu (2007)
Jijia river catchment (Moldavian Plateau)	100.0	49.5	34.6	19.0	12.0	5.5	3.5	Ioniţă (2000), Rădoane, Rădoane (2001)
Barlad river catchment (Moldavian Plateau)	100.0	52.0	31.1	17.0	8.0	4.9	4.0	Ioniţă (2000), Rădoane & Rădoane (2001)
Oltet river catchment (Getic Subcarpathians and Piedmont)	100.0	82.0	66.0	34.0	30.0	23.0	18.6	Ichim et al., (1994), Rădoane & Rădoane (2003)
Topolog river catchment (Getic Subcarpathians and Piedmont)	100.0	55.0	34.0	28.0	25.0	20.0		Rădoane N et al., (1999)
Jiu river catchment, effects of mining	100.0	99.0	97.0	96.5	96.0	95.5	95.0	Rădoane N et al., (1995)
Small catchments on the right side hillslope of Olt river, downstream of Rm. Valcea (Getic Subcarpathians and Piedmont)	100.0	81.0	62.0	46.0	40.0			Rădoane M et al., (1992)
Arges river catchment, upstream of Oiesti Lake(Getic Subcarpathians and Piedmont)	100.0	82.0	70.0	60.0	55.0	50.0	42.3	Ichim et al., (1994)
Bonţu river catchment, upstream of Ştiucii Lake (Transylvanian Plain)	100.0	85.0	15.0	6.24				This study

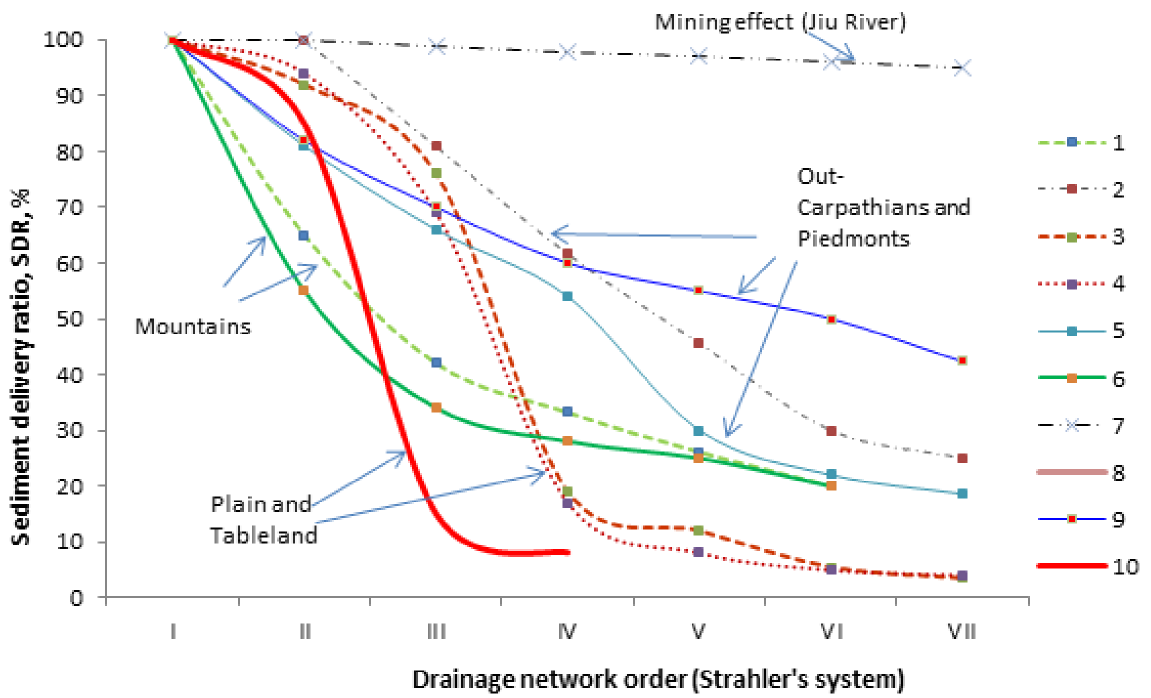

Figure 10. The relationship between the sediment delivery ratio and the drainage network order (Strahler's system) in several key areas in Romania: 1. Small catchments from flysch mountain area; 2. Catchments from the Moldova and Curvature SubCarpathians; 3. Jijia drainage basin (Moldavian Tableland); 4. Bârlad drainage basin (Moldavian Tableland); 5.Olteț drainage basin (piedmont area); 6.Topolog drainage basin; 7.Jiu drainage basin (mining effect); 8. Small catchments, Olt River left side (piedmont area); 9. Argeş River, upstream Oieşti Reservoir; 10.Bonțu drainage basin (upstream of Ştiucii Lake).

The variability of SDR curves shown in the diagram in figure 10 is maximal in the case of Jiu drainage network, whereby we documented an extremely high sediment load resulting from the coal ore washing (Rădoane N. et al., 1995), such that the delivery ratio reached 95% regardless of the river order (Strahler's system). Under natural conditions, such an SDR curve is not achievable; however, the anthropogenic interference (e.g. through mining activities) can also result in this kind of outcome.

To conclude, the results of the sediment budget analysis in a representative area pertaining to the Transylvanian Plain are instrumental in understanding the role of sediment storages and their archive capacity for gaining knowledge on the palaeoenvironment in this region of Romania. Whether it is the sediments stored in the floodplain of Someşu Mic River (Perșoiu&Rădoane, 2011), paleosols sequences from Someşu Mic terraces or laminated lacustrine sediments from Ştiucii Lake (Feurdean et al., 2013), the results yielded thus far for the Late Quaternary, and particularly Holocene time scale, are rather encouraging for this area of Europe. As several key moments in the palaeoevironmental changes in NW Romania have already been marked on this time scale, we believe the sediment archive of Bonțu stream can make a relevant contribution to a highly detailed sediment budget for the Holocene, which would further result in reliable conclusions regarding the geomorphological activity during certain periods.

Aknowledgement

This research is part of a project funded by the Fund for Scientific Research - Romania (research project PN-II-ID-PCE-2011-3). Also, this paper has been financially supported within the project entitled „SOCERT. Knowledge society, dynamism through research", contract number POSDRU/159/1.5/S/132406. This project is co-financed by European Social Fund through Sectoral Operational Programme for Human Resources Development 2007-2013. Investing in people!". The authors would also like to thank the several Msc. students in physical geography for their assistance during field work.

REFERENCES

Chorley, R.J., Schumm, S.A. & Sudgen, D.E., 1984. *Geomorphology*. Methuen, London 605 pp.

Ciupagea, D, Pauca, M. & Ichim, Tr. 1970. *Geology of the Trasylvania Depression* (in Romanian). Editura Academiei RS Romania, 256 pp.

Dietrich, W.E. & Dunne, T., 1978. *Sediment budget for a small catchment in mountainous terrain.* Z.

Geomoph. NF, Berlin-Stuttgart, 191-206.
Dumitriu, D., 2007. *Sediment system of the Trotuș drainage basin* (in Romanian). Editura Universităţii din Suceava, 259 pp.
Ferro, V. & Minacapilli, M., 1995. *Sediment delivery processes at basil scale.* Journal of Hydro. Sci 40. 703-717.
Feurdean, A., Liakka, J., Vannière, B., Marinova, E., Hutchinson, S.M., Mosburgger, V. & Hickler, T., 2013. *12000-Years of fire regime drivers in the lowlands of Transylvania (Central-Eastern Europe): a data-model approach.* Quaternary Science Reviews 81: 48-61.
Filipescu, M., 1950. *Premature aging of drainage network in the southern Moldova and its consequences* (in Romanian). Natura nr. 5, București. 7-12.
Fryirs, K. & Brierley, G.J., 1999. *Slope–channel decoupling in Wolumla catchment, New South Wales, Australia: the changing nature of sediment sources following European settlement*. Catena 35, 41–63.
Gârbacea, V., 1996. *Remarques sur le relief de "glimee" en Roumanie.* Geografia Fisica e Dinamica Quaternaria, vol. 19, 219-221.
Goudie, A.S. (ed), 1990. *Geomorphological Techniques. Second edition*. Allen and Unwin, London, 570 pp.
Ichim, I., 1986. *Sediment system* (in Romanian). Lucrarile Simpozionului provenienta si efluenta aluviunilor, I, Piatra Neamt, 1 - 31.
Ichim, I., Rădoane, M., Rădoane, N., Grasu, C. & Miclăuş, C., 1998. *Sediment dynamics. Application to Putna basin drainage* (in Romanian), Editura tehnică, București, 200 pp.
Ichim, I., Rădoane, M., Rădoane, N. & Catana, C., 1994. *Sediment budget from the Argeș drainage basin (Vidraru dam-Oești reservoir).* A geomorphological approach. Revue Roumaine de Geographie, Tom 38, București, 101-108.
Ichim, I., Rădoane, M., Rădoane, N., Grasu, C. & Cochior, C., 1994. *Sediment budget of Olteț drainage basin* (in Romanian). Lucrările sesiunii ştiinţifice anuale, Institutul de Geografie al Academiei. 139-144.
Ioniţă, I., 2000. *Applied geomorphology. Processes of hilly region degradation* (in Romanian). Editura Universității "Al. I. Cuza" lasi, 250 pp.
Ioniță, I., Rădoane, M. & Mircea, S., 2006. *Romania.* In: Boardman J, Poesen J (eds), *Soil erosion in Europe*, Wiley, Amsterdam-London-New York, 155-166.
Klimaszewski, M., 1990. *Thirty years of geomorphological mapping,* Geographia Polonica, 58, 11-18.
Lu, H., Moran, C.J. & Prosser, I.P., 2006. *Modelling sediment delivery ratio over the Murray Darling basin.* Environment Modelling and Software, vol.21, issue 9, 1297-1308.
Mac, I., 1997. *Type of landslides from the Transylvanian Depression with differentiated effects on the morphology of slopes.* Studia Univ. Babeș-Bolyai, Seria Geopraphya, XLII, No. 1-2, 5-14.
Mac, I., Idu, D.P., Mayer, A., Ciangă, N. & Sorocovschi, V., 1987. *Trasylvania Plain* (in Romanian). in Geografia României, vol. III, Carpații Românești și Depresiunea Transilvaniei. Editura Academiei, R. S. România, București. 541-547.
Morariu, T. & Gârbacea, V., 1968. *Deplacements massifs de terrain de type glimee an Roumanie.* Revue Roumaine de Geologie, Geographie, Geophysique, Serie de Geographye, tome 12 No.1-2, Editura Academiei București. 7-16.
Moțoc, M., 1983. *Average rate of soil erosion in R.S.R.* (in Romanian). Bul. inf. ASAS, nr. 13, București, 47-65.
Notebaert, B., Verstraeten, G., Rommens, T., Vanmontfort, B., Govers, G. & Poesen, J., 2009. *Establishing a Holocene sediment budget for the river Dijle*. Catena, 77, 150–163.
Parsons, A.J., Wainwright, J., Brazier, R.E. & Powell, D.M., 2006. *Is sediment delivery a fallacy?* Earth Surface Processes and Landforms 31 (10), 1325–1328.
Paucă, M., 1977. *Drainage network of the Someș Block-Genesis and evolution* (in Romanian). Studii și Cercetări de Geologie, Geofizică, Geografie, Tomul XXIV, nr.2, 179-189.
Perşoiu, I. & Rădoane, M., 2011. *Spatial and temporal controls on historical channel responses – study of an atypical case: Someşu Mic River, Romania*. Earth Surf. Process. Landforms 36, 1391–1409.
Pop, Gr., 2001. *Transylvania Depression.* Editura Presa Universitară Clujeană, Cluj-Napoca, Romania, 274pp.
Popa, A., Stoian, Gh., Popa, G. & Ouatu, O., 1984. *Arable land soil erosion controlling* (in Romanian). Editura Ceres, București. 189pp.
Popa, N., Margineanu, R., Filiche, E. & Petrovici, G., 2006. *Estimating soil erosion rates by using conversional models. A comparative study between simulated and measured on runoff plots data*. Lucrări ştiinţifice, Vol. 49, Seria Agronomie, Iasi, 11-22.
Popa, N., Nistor, D., Filiche, E. & Petrovici, G., 2013. *Studies on runoff and erosion rates in Eastern Romania.* Proceedings of the 1st CIGR Inter - Regional Conference on Land and Water Challenges Bari - Italy, 10-14 Sept. 2013. 9pp.
Pujină, D., 2008. *Landslides* (in Romanian). Performantica, Iasi, 145pp.
Rădoane, M., 2004. *Landform dynamics in the Izvoru Muntelui Reservoir* (in Romanian), Editura Universității Suceava, 199 pp.
Rădoane, M. & Ichim, I., 1987. *Problem of sediment delivery ratio and drainage network order* (in Romanian). Hidrotehnica, 32,2, 44-49.
Rădoane, M., Ichim, I., Rădoane, N., Miclăuș, C. & Grasu, C., 1992. *Sediment budget in small catchments from the Olt Valley* (in Romanian). Lucrările celui de-al IV-lea simpozion

”Proveniența și efluența aluviunilor” (supliment), Piatra Neamț, 208-219.

Rădoane, M., Rădoane, N., Ichim, I. & Surdeanu, V., 1999. *Gullies. Forms, processes and evolution* (in Romanian). Presa Universitară Clujeană, 266 pp.

Rădoane, M. & Rădoane, N., 2001. *Soil erosion and sediment transport in Jijia and Barlad drainage basins* (in Romanian). Revista de Geomorfologie, Bucureşti, vol. 3, 73-86.

Rădoane, M. & Rădoane, N., 2005. *Dams, sediment sources and reservoir silting in Romania*. Geomorphology 71, 112-125.

Rădoane, N., 2002. *Geomorphology of small catchments* (in Romanian). Editura Universităţii Suceava, 255 pp.

Rădoane, N., Rădoane, M., Ichim, I. & Miclăuş, C., 1995. *Mining influences on the sediment transport along Jiu River, Sadu upstream* (in Romanian). Studii si cercetari de geologie, geofizica si geografie, seria Geografie. XLII, 23-31.

Rădoane, N., Rădoane, M., Ichim, I., Grasu, C. & Miclăuş, C., 1997. *Sediment sources and sediment transport in the Bâsca Chiojdului drainage basin* (in Romanian). Analele Universității Ștefan cel Mare Suceava, VI, 33 - 48.

Rădoane, N., Rădoane, M., Ichim, I. & Miclăuş, C., 1999. *Contributions to the knowledge of the sediment transport in the Topolog drainage basin* (in Romanina). Analele Analele Universității Ștefan cel Mare Suceava, VIII, 11 - 22.

Rădoane, N. & Rădoane, M., 2003. *Geomorphological research for assessing Olteţ river channel as sediment source* (in Romanian). Analele Universităţii Ștefan cel Mare, Suceava, X, 27-35.

Richards, K. 2002: *Drainage basin structure, sediment delivery and the response to environmental change.* In: Jones, S.J.; Frostick, L.E. (eds.) Sediment Flux to Basins: Causes, Controls and Consequences. The Geological Society of London Special Publication 5(191): 149-160.

Reid, L.M. & Dunne, T., 2003. *Sediment budgets as an organizing framework in fluvial geomorphology*. In: Kondolf, M.G., Piégay, H. (Eds.), Tools in Fluvial Geomorphology. Wiley, 463–500.

Roehl, J.E., 1962. *Sediment source areas and delivery ratios influencing morphological factors*. Int. Assoc. Hydro. Sci. 59, 202-213.

Sandulache, Al. & Buta, I., 1963. *Some hydrological data on Sîntejude and Știucii Lakes from lower Fizeș drainage basin (Transylvania Plain)*(in Romanian). Probleme de Geografie, vol. 9, Academia R.P. Române, 306-314.

Savu, Al., 1980. *Transylvania Depression (Physiographic regioning), Point of view*(in Romanian). Studia Univ. Babeș-Bolyai, XXV, 2, Cluj-Napoca, Romania. 5-10.

Slaymacker, O., Souch, C., Menounos, B. & Filippelli, G., 2003. *Advances in Holocene mountain geomorphology inspired by sediment budget metodology*, Geomorphology, 55: 305-316.

Sorocovschi, V., Konecsny, C. & Nasaleanu, I., 1992. *Suspended sediment transport in higher part of the Mures drainage basin* (in Romanian), Lucrarile celui de-al IV-lea Simpozion Provenienta si efluenta aluviunilor (supliment), Piatra Neamt, 89-106.

Strahler, A.N., 1957. *Quantitative analysis of watershed geomorphology*. Transac American Geophysical Union, vol., 38, 913-920.

Surdeanu, V., Moldovan, M., Anghel, T., Buimagă-Iarinca, Șt. & Pop, O., 2011. *Spatial distribution of deep-seated landslides (glimee) in the Transylvania basin*. Studia Univ. babeș-Bolyai, Seria Geographya, fasc. 2., 3-9.

Șerban, Gh. & Sorocovschi, V., 2003. *Știucii Lake – Transylvania Plain (*in Romanian*).* Studia Univ. Babeș-Bolyai, Geographia, XLVIII, 1, Cluj-Napoca, 47-57.

Walling, D.E., 1983. *The sediment delivery problem.* In: I. Rodriguez-Iturbe and V.K. Gupta (Guest-Editors), Scale Problems in Hydrology. J. Hydrol.65: 209-237.

Wischmeier, W. & Smith, D., 1965. *Predicting rainfall erosion losses. A guide to conservation planning.* US Department of Agriculture Handbook. No. 537. 58pp.

Wolman, M.G., 1977. *Changing needs and opportunities in the sediment field*. Water Resources Research, v. 13(1), 50-54.

Received at: 10. 02. 2014
Revised 07. 07. 2014
Accepted for publication at: 24. 07. 2014
Published online at: 01. 08. 2014