STUDY OF HANGING VALLEY IN LOESS-PALEOSOIL SEDIMENTS WITH SOIL EROSION ASSESSMENT USING NUCLEAR AND EROSION POTENTIAL METHODS

by

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This paper is dealing with soil erosion assessment using two different approaches: nuclear model and erosion potential method, also known as Gavrilovic's method. Complex valley systems on Titel Loess Plateau were selected for investigation. Radiocaesium is favored in many studies as an optimal erosion tracer due to its relatively long half-life, negligible renewal in the environment and strongly binding ability onto soil particles. The use of gamma-spectrometry in environmental testing laboratories acts as a precise and fast measurement technique for determination of ^{137}Cs activity concentrations, without the need for complicate preparation of samples. Annual erosion and deposition rates were estimated according to three conversion models for uncultivated land: the profile distribution model with two years of dominant fallout of ^{137}Cs (1963 and 1986) and the diffusion and migration model using WALLING software. The applied nuclear models were validated by comparison with erosion potential model which is the most relevant empirical model for erosion processes in torrent valleys. The obtained results indicate a good agreement with overall low values of average annual soil erosion rates on all soil profiles in the investigated area. Correlation analysis has determined the different influence of slope, terrain curvature, and vegetation index on the erosion models.

Key words: hanging valley, soil erosion, radiocaesium, gamma-spectrometry, Gavrilovic's method, Titel Loess Plateau

INTRODUCTION - EVOLUTION OF HANGING VALLEYS ON TITEL LOESS PLATEAU

Titel Loess Plateau (TLP) is situated near the confluence of the Tisza and Danube rivers in the southern central part of the Autonomous Province of Vojvodina, Serbia, fig. 1. This elliptical loess island extends between the settlements Mošorin (NW), Titel (SE), Lok (S), and Vilovo (SW). Loess horizons are dusty deposits that have accumulated during Aeolian activity during the last five glacial and interglacial periods in the Pleistocene and throughout the Holocene (approximately 600 000 years). In the conditions of warm and humid interglacial climate, fossil soils were formed. At the extreme southeastern part of the plateau, about 200 m SE from the Titel settlement the geo-locality Loess Pyramid is located with two hanging valleys (or gullies) which are the subject of our research.

All the recent hanging valleys on the TLP were formed during the Holocene by the same processes. In the first phase of evolution, it is assumed that valley's lower part was at a slight slope in relation to the Tisza River, than it is today. The position of the Tisza riverbed then, would be as shown in fig. 2. A. With the fluctuation of the climate and its gradual transition to a wetter and warmer phase, the level of the Tisza River increased significantly, which caused the migration of

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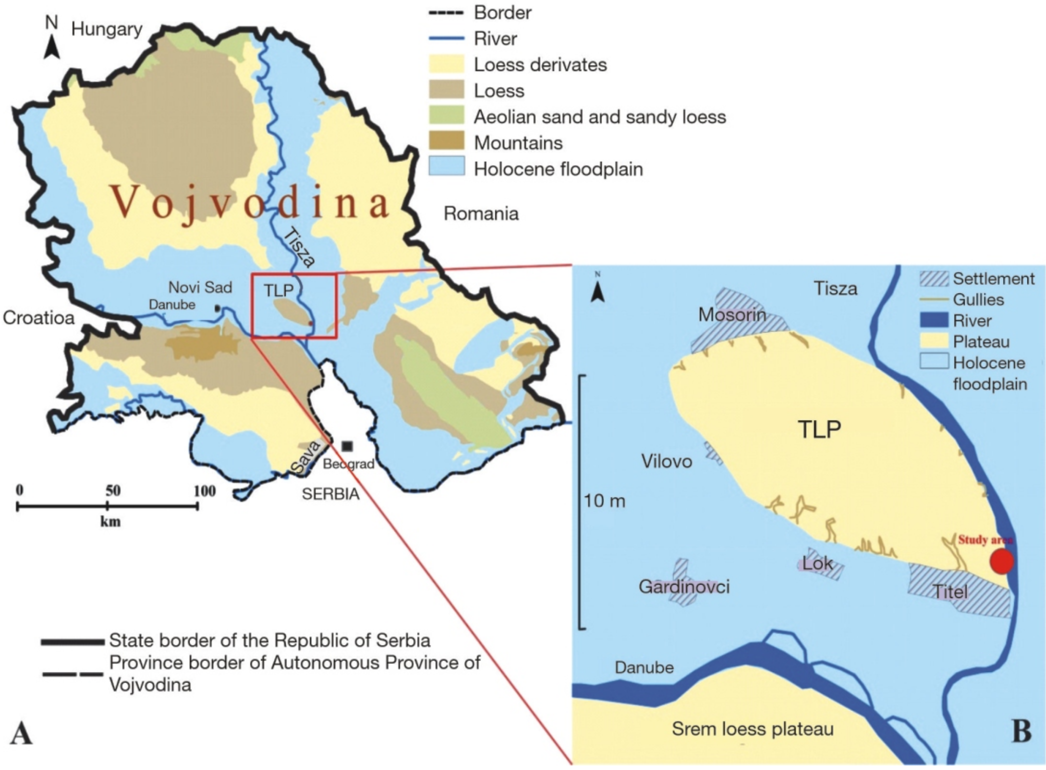

Figure 1. The geographical position of TLP on the geomorphological map of the Autonomous Province of Vojvodina (A) with marked position of study area (B) [1], modified

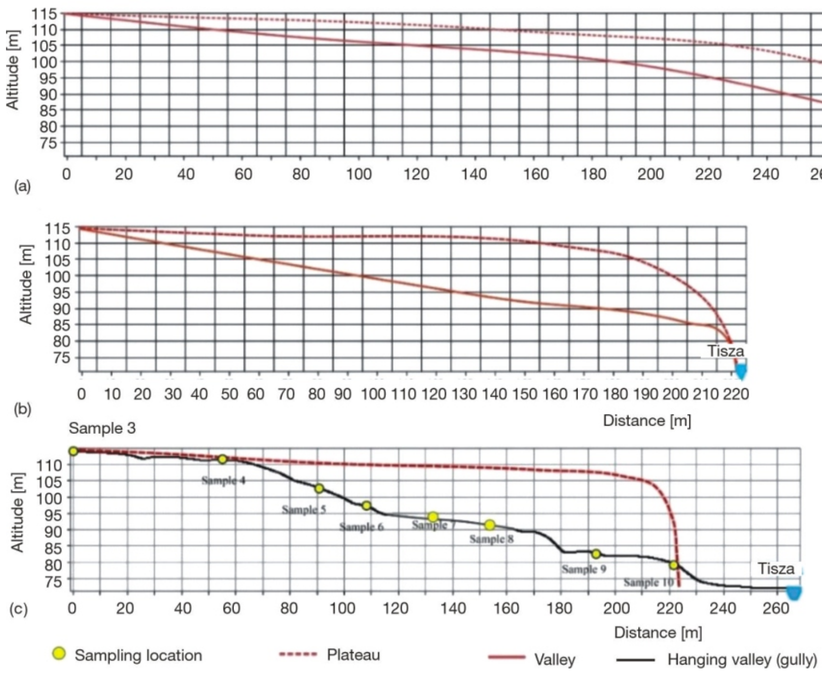

Fig 2. Schematic illustration of evolution of the hanging valley on TLP; the assumed appearance of the valley before the erosion of the Tisza River (A), the reduction of the length of the valley by the erosion of the Tisza River (B) and the current appearance of the valley (C) [2]

its bed in the direction of TLP. Due to long-term vertical erosion, the Tisza riverbed is leveled, and the lower part of the valley is washed away by lateral erosion, fig. 2(b). After the gradual lowering of the water level in the last phase, there was a re-migration of the Tisza riverbed towards its original position, fig. 2(c). As a result, two new relief units were formed – a hanging valley at the site of the slope and a small alluvial plain at the site of the Tisza riverbed. Such a relationship of relief members has been maintained to these days [2].

The two hanging valleys at geo-locality Loess Pyramid were tributaries of proto valley orientated to the larger Titel alluvial fan with the same orientation as the surrounding big valley (today gullies) in the vicinity of Titel settlement. After the appearance of a second phase, fig. 2(b) with intensive fluvial erosion by the Tisza River, the erosion destroyed most of this proto valley and initiated a change in drainage from south to east. In this way, two tributaries of the former proto valley are drained directly into the Tisza River [3, 4]. As the process of fluvial erosion progressed, these valleys became closer to each other, especially in its upper part, due to the intense lowering of the common watershed, deepening their beds, and regressively cutting [5]. The final phase of morphogenesis of this feature involves the latest Tisza River erosion event, which allowed the two large V-shaped hanging valleys [3, 4], fig. 2(c). With the transition to the drier phase, where the proluvial and pluvial erosion are dominant, these valleys were transformed into gullies. The results of geochemical analysis [6] confirmed this assumption of which indicates that the loess pyramid is not a product of sediment accumulation by these hanging valleys.

In older literature [5, 7], these two hanging valleys are known as the Northern and Southern valleys. Based on current remote sensing analyzes and field research, it has been established that in the case of the Northern valley, the process of cutting the riverbed is still present, which is why, compared to the South valley, its longitudinal profile of the riverbed is more inconsistent. In contrast, the bed of the South valley is not cut. Due to these characteristics, the names – Recent lower gully (referring to the northern gully) and Fossil upper gully (referring to the southern gully), fig. 3 are more appropriate. Between the gullies is a low watershed with an average 2 m width which widens slightly towards the Loess Pyramid.

Gullies on TLP represent relict remains on the edge of the plateau of former valleys through which it was drained into the Tisza or Danube rivers. As such, they represent the largest forms of relief on the plateau, so they are the largest sources of sediments as well as their transporters [8, 9]. The main difference between the mentioned relief members is the degree of anthropogenic influence which changed their morphological structure. Since in this paper we decided to investigate soil erosion on the example of a well-studied gully from the aspect of its genesis and evolution [5, 7] in which human influence is negligible, this paper represents a contribution to the study of erosion of uncultivated soil, typical for gullies.

The nuclear models with the determination of artificial origin radionuclide ^{137}Cs in soil, were used to quantify the rates of erosion processes. Through precipitation, this radionuclide was strongly bind to the fine soil particles in the top layer and can thus be considered as being essentially non-exchangeable [10-12]. The concentration of caesium in topsoil decreases in deeper layers under the influence of diffusion, mechanical or chemical removal [13].

STUDY AREA

The position of the TLP between the Tisza and the Danube contributes to the mitigation of climatic extremes in the conditions of moderate continental climate. The average annual rainfall is 602 mm. The lowest precipitation is in October (average 33 mm), while their maximum is in June (average 82 mm). In summer, rain usually falls in the form of rainstorms and

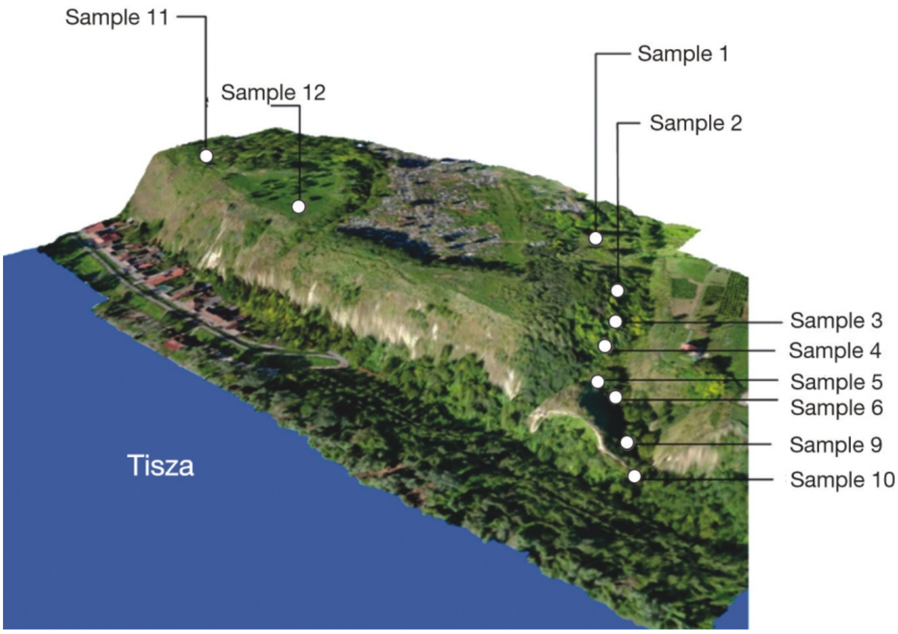

Figure 3. The study area with sampled soil profiles

Table 1. Topographic characteristics of the sampling locations with a description of the vegetation cover

Sample	Latitude [º N]	Longitude [º E]	Altitude [m]	Slope [º]	Vegetation
1	45.21011	20.30824	118	2.56	Grass
2	45.21050	20.30857	116	5.11	Grass
3	45.21068	20.30902	112	9.66	Grass
4	45.21074	20.30927	107	12.77	Grass
5	45.21079	20.30959	102	13.17	Poor grass
6	45.21096	20.30964	101	12.96	Poor grass
7	45.25142	20.15698	97	0.47	Grass
8	45.25157	20.15680	97	1.26	Grass
9	45.21125	20.309833	106	17.01	Poor grass
10	45.21150	20.310028	99	17.23	Ivy
11	45.208444	20.310111	131	21.04	Grass
12	45.207194	20.310222	127	12.40	Grass

much of it evaporates. It happens that the total monthly amount of atmospheric sediments falls in just one day. At the end of spring and the beginning of summer, there is enough precipitation, which is important for the development of vegetation [2].

To investigate soil erosion processes in the valley system of TLP, a total of 12 soil profiles were sampled in the vicinity of Loess Pyramid geo-locality near Titel settlement during 2017/2018. The geographic position of TLP and the field view of the study area with sampling points are presented in fig. 3 with topographic characteristics and vegetation cover description of locations given in tab. 1.

Samples 11, 12, and 1 are located outside the gully system and were selected as potential reference soil sites by field observation. The remaining (2-6, 9, and 10) profiles were sampled along the gully successively towards the bank of the Tisza River, from which profiles 2-5 were sampled at the watershed and profiles 6, 9, and 10 were sampled in the lower part of the northern gully. The last profile 10 was sampled on the floodplain material of the gully under the assumption that this point would show the zone of accumulation of material from the gully fig. 2(c). Profiles 7 and 8 were sampled on small, terraced parts of TLP in Vilovo settlement, also as reserved, reference profiles.

METHODOLOGY OF INVESTIGATION

All the samples were prepared for gamma-spectrometry analysis according to the standard procedure (drying to the constant mass, grinding, and homogenously packing in plastic boxes of cylindrical geometry 67 mm $\times$ 30 mm). Determination of ^{137}Cs activity concentrations was done based on gamma-spectrometry measurements performed with two HPGe detector systems in the lead passive shield at the Laboratory for radioactivity and dose measurements, Faculty of Sciences, University of Novi Sad, Serbia. On both detectors, manufactured by ORTEC (relative efficiency 32.4 %) and Canberra (relative efficiency 100 %) typical time of measurement yielded 80 000 s [14]. All the samples of one soil profile were measured on the same detector. Efficiency calibration of detection systems was carried out with certified reference material – a mixture of radionuclide gamma emitters in the resin matrix of cylindrical geometry Cert.No:1035-SE- 40001-17. Gamma spectra of soil samples were acquired and analyzed using the GENIE 2000 Spectroscopy System Software program, manufactured by Canberra USA. Gamma ray emissions in samples, at 662 keV, coming from the presence of ^{137}Cs, were investigated [15].

Using the conversion models for uncultivated soil (Walling and He, 1999, 2001), the measured ^{137}Cs inventories in Bqm^{-2} were converted to annual soil rates in tha^{-1} per year. The standard Profile Distribution Model (PDM) assumes that the total deposition of ^{137}Cs from the atmosphere occurred in 1963 and that the vertical distribution of ^{137}Cs in the soil profile is time-independent. The erosion rate Y for the observed erosion site (if total ^{137}Cs inventory Au [Bqm^{-2}] is less than the reference inventory A_{ref} [Bqm^{-2}]) can be estimated as

$$Y = \frac{10}{(y_s - 1963)p} \ln\left(1 - \frac{X}{100}\right) h_0 \tag{1}$$

where Y [tha^{-1}] is the annual soil loss, y_s – the year of sample collection, X – a percentage of ^{137}Cs loss in total inventory in respect to the local ^{137}Cs inventory (defined as $[(A_{\text{ref}} - A_{\text{u}})/A_{\text{ref}}$ 100. The coefficient that describes a profile shape h_0 [kgm^{-2}] can be estimated from vertical exponential distribution of ^{137}Cs mass concentration with depth for the reference profile [16]

$$A'(x) = A_{\text{ref}} \left(1 - e^{-\frac{x}{h_0}}\right) \tag{2}$$

where $A'(x)$ [Bqm^{-2}] is the amount of ^{137}Cs above the depth x and x [kgm^{-2}] is the mass depth from soil surface

When choosing a conversion model, authors were guided by the fact that the Chernobyl accident is more important compared to nuclear testing in terms of the origin of ^{137}Cs presence in the soil layers for our region (Serbia). For that reason, the annual values of soil loss were calculated using the same model but with year 1986 as a year of dominant fallout.

The previously described model of vertical distribution of radiocaesium gives approximate values of the erosive processes rates in the case of uncultivated soil. A far more realistic approach to erosion investigation is provided by a model that considers the migration of ^{137}Cs along the vertical soil profile over time [17]. This diffusion and migration model (DMM) is characterized by three variables: the annual effective diffusion coefficient D [kg^{2}m^{-4}], the annual migration rate V [kgm^{-2}] and relaxation mass depth of the ^{137}Cs initial distribution in topsoil H [kgm^{-2}]

$$C_u(t) \quad \frac{I(t)}{H} \quad \int_0^{t\ 1} \frac{I(t\ )\mathrm{e}^{\ R/H}}{\sqrt{D\ (t\ \ t\ )}} \mathrm{e}^{\ V^2(t\ \ t)/[4D\ \ \lambda(t\ \ t\ )]} \tag{3}$$

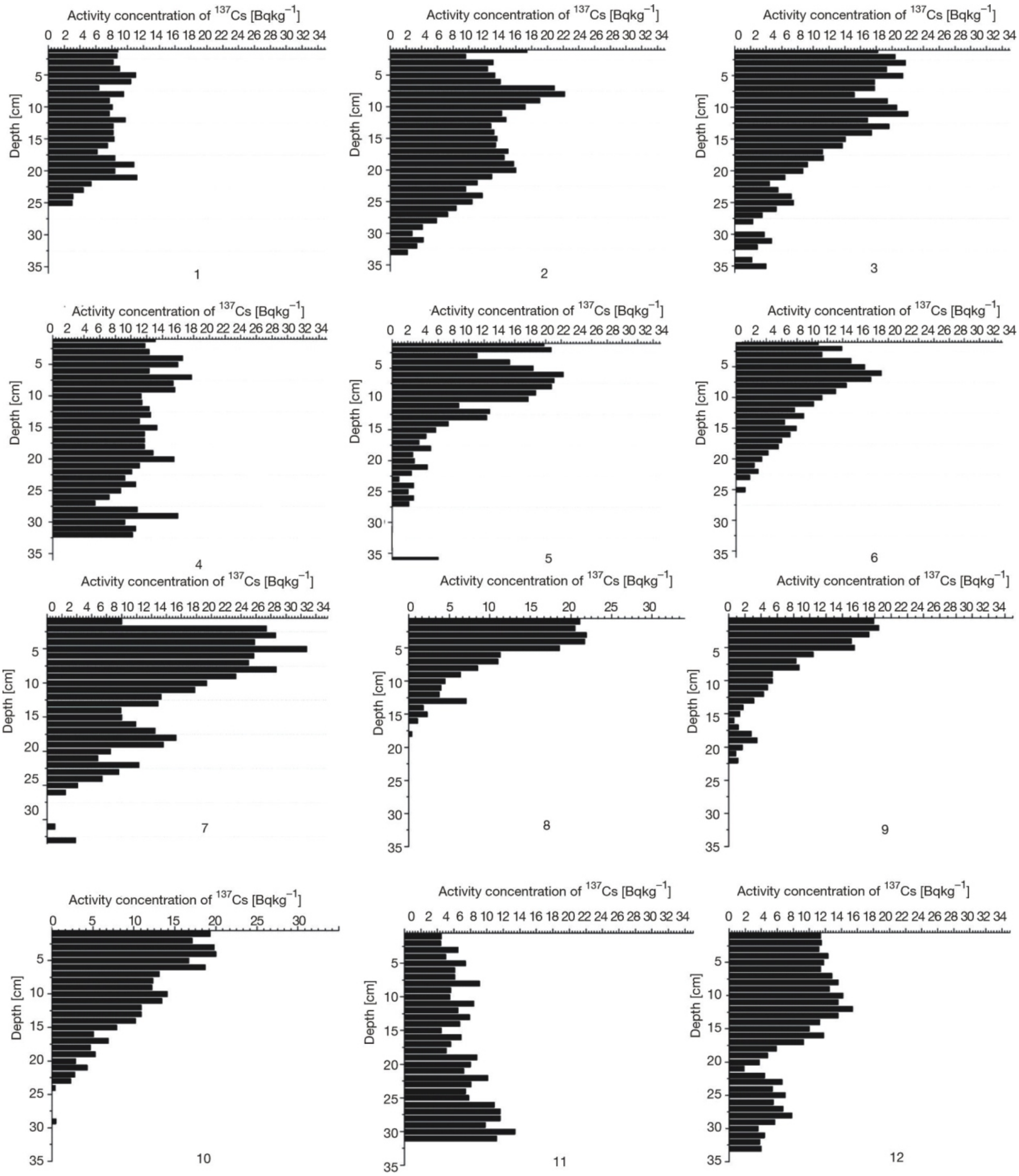

Figure 4. Vertical distributions of ^{137}Cs activity concentrations [Bqkg^{-1}] for each sampled profile (total 12 soil profiles)

where $C_u(t)$ [$Bqkg^{-1}$] is the time variation of the ^{137}Cs concentration in surface soil, $I(t)$ [Bqm^{-2}] – the annual ^{137}Cs deposition flux and R [kgm^{-2}] – the annual erosion rate.

To calculate annual soil erosion loss, Walling excel add-in program was used with 80 % of total Chernobyl fallout contribution for our region which is in good agreement with numerous references [18-20]. For the relaxation depth H, diffusion coefficient D and downward migration rate V, the values recommended by program [21] were adopted and implemented.

RESULTS OF GAMMA-SPECTROMETRY ANALYSIS AND QUANTIFICATION OF ANNUAL SOIL EROSION RATES

The results of gamma spectrometry analysis are presented graphically for 12 soil profiles in the frame of the vertical distributions of radiocaesium concentrations through the soil layers, fig. 4(1)-4(12). In order to convert inventory values [Bqm^{-2}] to annual erosive rates [tha^{-1}], it was necessary to determine a reference point for the research area. Soil sample 1 which is beyond the gully system was claimed as a potential reference site. But its vertical distribution of radiocaesium, fig. 4(1) and low amount of ^{137}Cs inventory indicate erosion, fig. 5, so sample 1 is not a good candidate as a reference profile. The same mentioned characteristics led to the decision that soil samples 11 and 12 were also claimed as zones of erosion fig. 4(11) and 4(12); fig. 5. Hence, the possibility of soil sample 7 and 8 was brought into consideration as reference site.

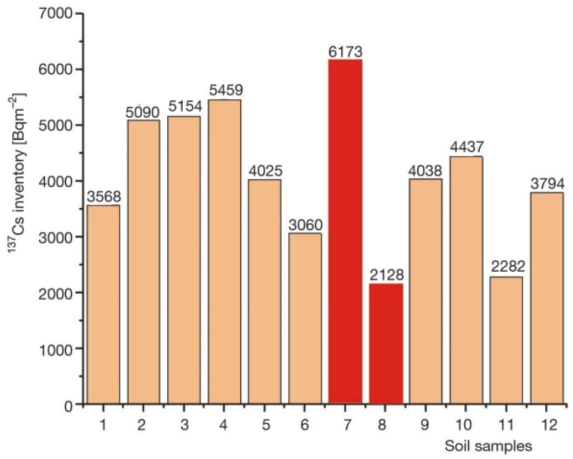

Figure 5. Total radiocaesium inventories for each soil profile

Profiles 7 and 8 were sampled in Vilovo on the terraced section at the edge of TLP close to cultivated area, fig. 6(a) and possible influence of erosion. The smallest

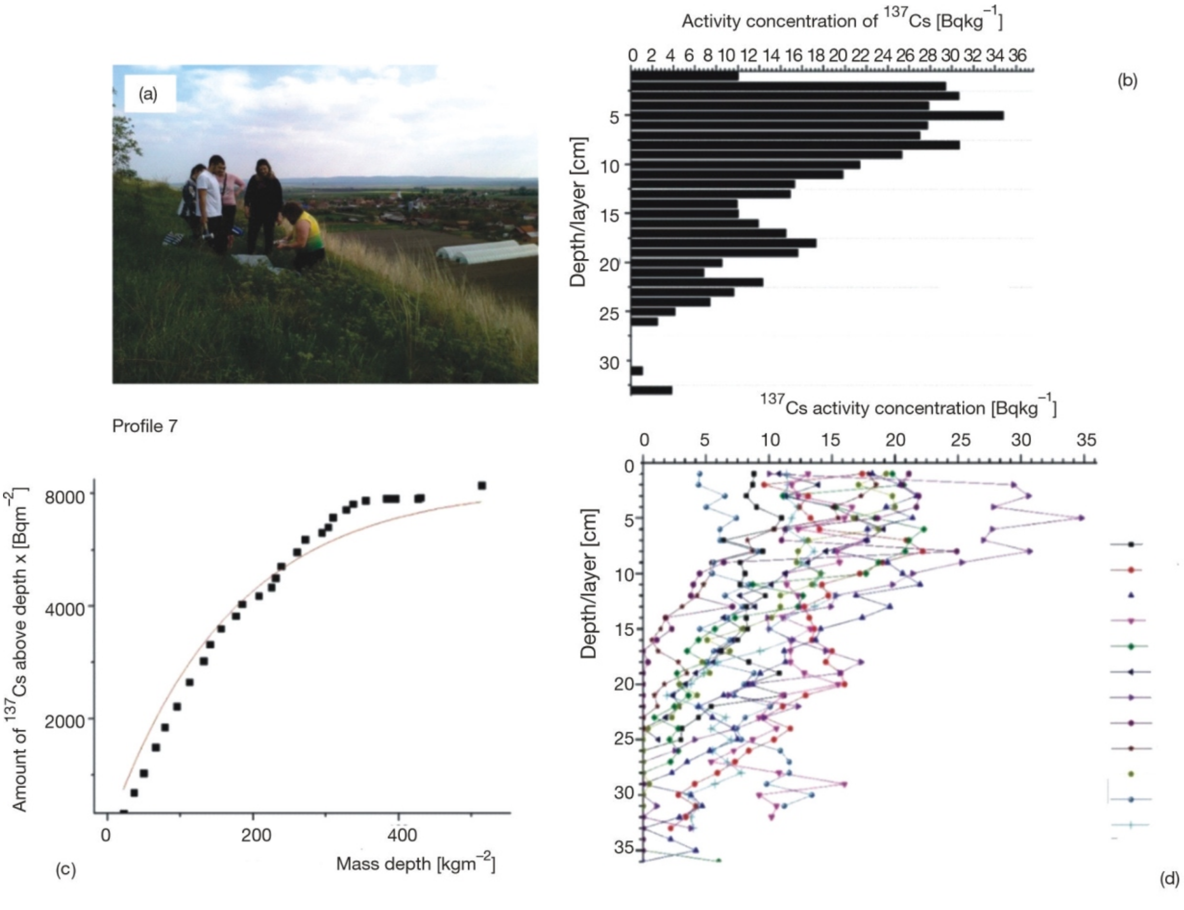

Figure 6. Position of reference site on a small terrace at the edge of TLP (a), vertical distribution of ^{137}Cs concentrations with depth (b), exponential function between amount of ^{137}Cs above depth x and mass depth (c), and vertical distribution of radiocaesium for each soil profile (d)

Table 2. Results of estimation for annual soil erosion using ^{137}Cs method with different conversion models: PDM with two years of dominant fallout (1963 and 1986) and the DMM

Profile	Y [tha^{-1}]		
	^{137}Cs method		
	PDM (1963)	DMM	PDM (1986)
1	–5.11	–3.90	–8.89
2	–1.8	–1.60	–3.13
3	–1.68	–1.50	–2.92
4	–1.15	–1.00	–2.00
5	–3.99	–3.20	–6.94
6	–6.54	–4.70	–11.38
9	–3.95	–3.10	–6.87
10	–3.08	–2.50	–5.36
11	–9.27	–6.00	–16.13
12	–4.54	–3.50	–7.90

caesium inventory for the profile 8, fig. 5 indicates erosion that jeopardizes the possibility of location 8 as a reference site. However, obtained good exponential fit between mass concentration ^{137}Cs [Bqm^{-2}] and mass depth [kgm^{-2}], fig. 6(b)-6(d), resulted with selection of profile 7 as the reference sample.

The results of the calculation of annual values of soil loss using three conversion models for radiocaesium are shown in the tab. 2.

The obtained results are in good agreement with the published results conducted at several locations in the Republic of Serbia: calculations of erosive processes by Petrović [22] on uncultivated soil in the valleys of Pčinja river and South Morava river using PDM and DMM, averaged values of –12.0 tha^{-1} per year and –4.0 tha^{-1} per year were obtained, respectively. The rates of erosive processes on five sampled soil profiles on uncultivated soil using PDM and DMM were calculated using the radiocaesium method. Erosion values range from –5.6 tha^{-1} per year to –28.0 tha^{-1} per year using PDM and –2.4 tha^{-1} per year to –8.9 tha^{-1} per year using DMM [22, 23].

It is surprising that profile 10 showed some erosion considering that this sampling point lies on the alluvial plain which was also covered by dense vegetation – ivy. To establish the reason for this result, the movement of the Tisza water level from 1986 to the present day was analyzed, fig. 7.

By analyzing the annual water level of the Tisa River, it was concluded that, starting from the Chernobyl accident, the water level varied considerably, and on a couple of occasions, the water level reached the absolute height of the point at which sample 10 was formed. So, the area under the position of sample 10 is disturbed by the Tisa River erosion too. Looking for a point of accumulation, it would be more realistic to perform in the Tisza riverbed, although this is also debatable because the finest particles, to which radiocaesium is usually attached, were probably taken away by water.

QUANTIFICATION OF ANNUAL DEPOSITION RATES USING THE GAVRILOVIC'S METHOD

In the seventies of the last century, Gavrilović developed an erosion potential model for analytical determination of erosive coefficients, quantification of total soil erosion, and average annual transport of sediments [25]. The model was created with the idea of developing adequate strategies in the control of erosive processes in forest areas and torrent valleys.

This empirical model is easy to use and suitable for implementation in cases where the input parameters are incomplete or do not exist. It is more applicable for erosion assessment of larger areas, rather than for smaller areas [26]. Unlike nuclear methods, this model is not focused on the erosive process itself (erosion or accumulation) but on the assessment of the total potential sediment yield and its transport in the basin. In addition, the model provides data on the intensity of erosion and identifies high-risk areas from the aspect of erosion problems. Field experiences indicate that the model is more applicable for areas of moderate to strong erosion, as opposed to areas of weaker erosive potential [27].

This method considers the geological and pedological characteristics of the terrain, topographic characteristics (slope), climatic characteristics (average annual rainfall and average annual temperature), and the way of land use. Climate data were taken from the Mošorin precipitation station for the period from

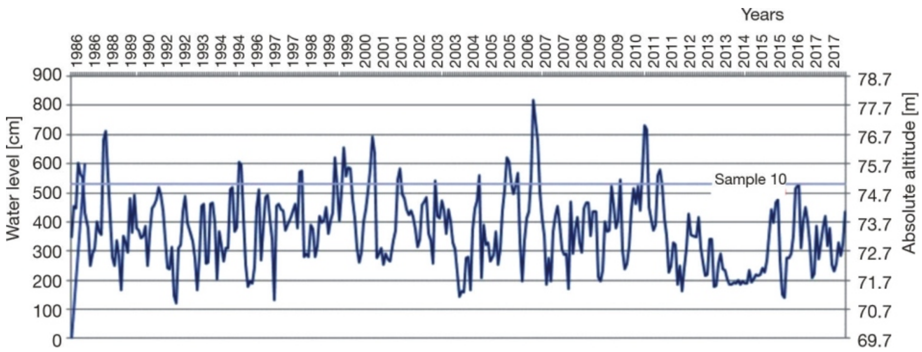

Figure 7. Fluctuations of the Tisza water level in time (from 1986 to 2017) [24]

1946 to 2018. Topographic data were taken from a slope map generated from the Digital Elevation Model at a scale of 1:12 000 in ArcMap 10.3.1.

The coefficient of soil resistance to erosion, X, (as a function of land use and vegetation coverage) quantitatively expresses the protection of the area from erosion. Its values are tabulated and range from 0.05 (lower limit of the class *Mixed and dense forests*) to 1.0 (upper limit of the class *Areas without plant cover*). The data source was a vector graphic of the study area The Corine Land Cover Data [28].

The coefficient of soil erodibility, Y, (as a function of geological and pedological characteristics of the investigated area) shows how susceptible the soil is to erosion. Its values are tabulated, ranging from 0.20 (lower limit of the *Resistance Rock* class) to 2.0 (upper limit of the class *Fine sediments and soils without erosion resistance*). The source of data on this coefficient was the geological map of Serbia in the scale of 1: 100 000, [29] and the pedological map of Serbia in the scale of 1:50 000 [30].

The coefficient, Φ represents the degree of pronounced erosion processes (visibly characterized) in the basin. Its values are tabulated, ranging from 0.10 (lower limit of the class *Limited erosion in the basin*) to 1.0 (upper limit of the class *Whole area affected by erosion*). The values of this coefficient that indicate the state of erosive processes were determined by field research as well as considering the coefficients X and Y [31].

In the combined expression (4), the values of erosive coefficients, Z, were calculated, based on which, the classification of erosion rates was performed for each location

$$Z \quad Y \; X(\Phi \quad I^{0.5}) \tag{4}$$

where the parameter Y is the coefficient of soil erodibility, X – the coefficient of land use, Φ – the degree of pronounced erosion processes, and I – the average slope of the terrain in percent [26, 32].

To facilitate the assessment and use of EPM coefficients, in addition to the original classifications [32, 33], a universal classification of land use, geological characteristics, and active erosive processes from the Corine Land Cover 2000 database was attached.

The annual specific sediment production, W_{sp}, [m^{3}km^{-2}], could be estimated by the following equation

$$W_{sp} \quad MZ^{1,5} \tag{5}$$

where M is the climate potential of erosion in the basin which is calculated as

$$M \quad TH_{year} \tag{6}$$

where T is the coefficient of temperature, which is evaluated from the equation

$$T \quad (t_a / 10 \quad 0.1)^{0.5} \tag{7}$$

where t_a represents annual air temperature [°C] and H_{year} [m^{3}km^{-2}] represents annual precipitation amount [34] and could be estimated from the equation

$$H \quad \frac{H_1 f_1 \quad H_2 f_2 \quad \cdots H_n f_n}{F\,!} \tag{8}$$

where $H_{1,2...n}$ are the annual precipitations between the hyetos, $f_{1,2....n}$ surface areas between the hyetos, and F is the basin area [25].

In order to the results of Gavrilovic's method be comparable with the results of radioactive methods, it is necessary to convert volume [m^{3}km^{-2}] into mass units [tha^{-1}], by multiplying with soil profile density ρ [kgm^{-3}] [34, 35]. The results obtained and compared in this way are presented in the tab. 3.

In accordance with the high values of the coefficient $\boldsymbol{Z}$ ($Z > 1.00$), all sampling points have excessive or very strong erosion characteristic for gullies. The average value of the erosion coefficient in the investigated area is 1.19.

DISCUSSION OF RESULTS

Based on the obtained results of Gavrilovic 's method, it is possible to make a comparison with the methods of radiocaesium. The tab. 4 presents the results of four models for estimating the erosion/deposition rates in the study area.

Erosion is the dominant process at all experimental sites. The EPM estimates soil losses in an area but does not give the actual value of erosion intensity

Table 3. Annual sediment production evaluation with estimation of EPM parameters

Profile	Y	Φ	X	I [%]	M	Z	ρ [kgm^{-2}]	W_{sp} [tha^{-1}]
1	0.5	0.8	0.9	4.47	89.71	1.31	4320.0	5.82
2	0.5	0.4	0.6	8.94	89.71	1.02	3110.0	2.86
3	0.5	0.4	0.6	17.02	89.71	1.36	3490.0	4.95
4	0.5	0.3	0.4	22.66	89.71	1.01	2390.0	2.18
5	0.5	0.3	0.4	23.40	89.71	1.03	3840.0	3.59
6	0.5	1.0	0.4	23.01	89.71	1.16	3730.0	4.18
9	0.5	1.0	0.4	30.59	89.71	1.31	3740.0	5.01
10	0.5	1.0	0.4	31.01	89.71	1.31	3600.0	4.86
11	0.5	0.6	0.4	38.47	89.71	1.36	3870.0	5.51
12	0.5	0.6	0.4	21.99	89.71	1.06	4100.0	4.00

Table 4. Comparative analysis of the annual soil erosion assessment resulted from different methods applied

Profile	Y [tha^{-1}]			
	^{137}Cs method			EPM
	PDM(1963)	DMM	PDM(1986)	
1	–5.11	–3.90	–8.89	5.82
2	–1.8	–1.60	–3.13	2.86
3	–1.68	–1.50	–2.92	4.95
4	–1.15	–1.00	–2.00	2.18
5	–3.99	–3.20	–6.94	3.59
6	–6.54	–4.70	–11.38	4.18
9	–3.95	–3.10	–6.87	5.01
10	–3.08	–2.50	–5.36	4.86
11	–9.27	–6.00	–16.13	5.51
12	–4.54	–3.50	–7.90	4.00

Table 5. Correlation analysis of results obtained by applying different models

	PDM(1963)	DMM	PDM(1986)	EPM
PDM(1963)	1			
DMM	0.99	1		
PDM(1986)	0.99	0.99	1	
EPM	0.57	0.59	0.57	1

or determines the type of erosive process, unlike the nuclear method in which a negative sign clearly identifies erosion and a positive value for the accumulation [35]. To determine the extent to which the results of the four models applied are interrelated, they were subjected to correlation analysis in SSPS program.

Based on the Pearson's coefficients of linear regression analysis, tab. 5, it can be concluded that EPM results have a positive moderate correlation with ^{137}Cs models. The best correlation was achieved with the DMM (r = 0.59), while with PDM (1986) and PDM (1963) a lower correlation coefficient was obtained (from r = 0.57), which was expected since the models do not take into consideration the subsequent land redistribution.

The relatively good agreement of the models indicates a satisfactory selection of the reference point.

Table 6. Universal annual soil loss classification in tha^{-1}

Erosion [tha^{-1}]	Erosion classification
<5	Very low
5-10	Low
10-15	Medium low
15-20	Medium
20-25	Medium-high
25-35	High
35-50	Very high
>50	Extremely high

As there is no specific categorization of the average annual value of the erosion by the nuclear method, the table of universal soil erosion categorization, tab. 6 was used for evaluation of the values obtained by these four models in tha^{-1} [36].

According to universal soil classification, all the results indicate a generally low average value of the erosion rate on an annual level. The highest values are noticeable in the PDM (1986) model and the least in the EPM, fig. 8.

The results of Gavrilović ́s method are in accordance with the results of three conversion models for the calculation of erosive processes by the radiocaesium method. A similar issue was addressed by Tošić *et al.* [37], in the neighboring Republic of Bosnia and Herzegovina, on the agricultural zone in the catchement of Drenova basin, where two sites were sampled (in the potential zone of erosion and potential zone of accumulation of sediments). The proportional model (PM) and the simplified version of the mass balance model (SVMBM) were used to estimate the mean soil loss, soil erosion and soil deposition redistributions rates. The results of the nuclear method are compared with the results of the Gavrilovic's method. The result of the proportional model is closer to the result of the conventional model, because the proportional model is a less sensitive model than the simplified version of the mass balance model. The best agreement was achieved for the point sampled in the potential accumulation zone where PM gives the erosion rate of 9.19 tha^{-1} per year, which is very close to

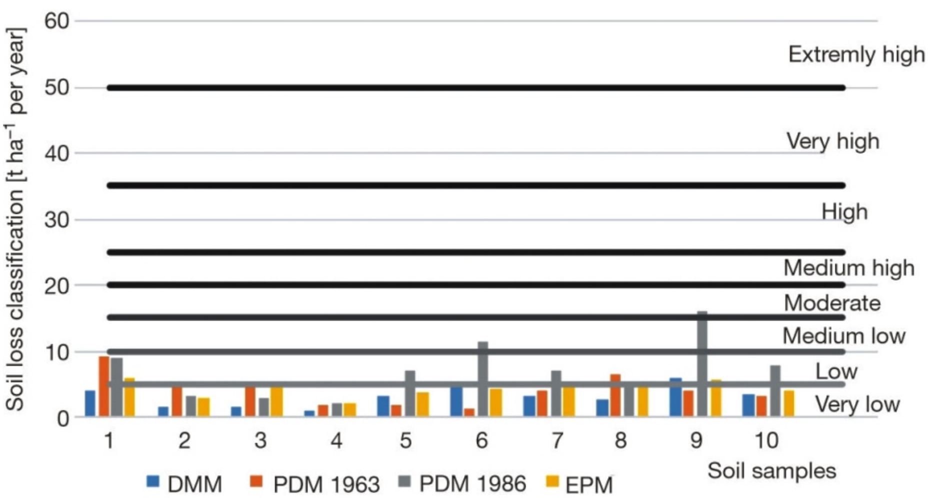

Figure 8. Comparative analysis of annual erosion using four conversion models

the value of 9.89 tha^{-1}per year, calculated by the Gavrilovic's method [37].

Calculations of annual land losses, in the case of all four models, are greater than 1 tha^{-1}, which indicates irreversible land losses, *i. e*, that the time required for self - renewal of land is 50 to 100 years [38]. One of the aims of this paper was to compare these results in order to validate the selected reference point (Vilovo 7). Using SSPS program, the results of four models were compared by *t*-test in order to examine the existence of statistical significance among the compared pairs (three pairs). The test results are shown in the tab. 7.

It was found that there is no significant difference in the confidence interval of $p = 0.05$ between the measured and estimated values, *i. e*., between the compared pairs of models. The results of the *t*-test confirm the previously made assumption that a good choice of the reference point has been made in the case of the radiocaesium method.

By analyzing some topographic factors (height, slope, profile and planar curvature, and normalized difference vegetation index – NDVI), it was concluded that in this study Gavrilovic's method is more sensitive to the character of terrain coverage, in contrast to the conversion models for radiocaesium which are more sensitive to slope size, tab. 8.

Like similar empirical models (USLE, RUSLE), the EPM can be characterized as a diagnostic tool that should be critically interpreted and combined with other techniques and methods whenever possible [35]. Empirical models simplify the phenomena through regressive relationships of experimental data that connect the statistically most relevant parameters. Because of their simplicity, the use of empirical models has been widely documented in the scientific literature. Such models usually provide a valuable approach for estimating soil erosion, if used in the same geomorphological environment where they were calibrated [39]. By applying geographic information systems GIS, it reduces the subjectivity of researchers by integrating different information layers to identify and classify certain parameters in the observed area [40].

Physical models (such as conversion models used in the conversion of annual land losses by the nuclear methods) usually require a significant amount of input and computational effort but, provide a mechanical description of erosive processes and estimate the interaction of each element, providing far more realistic data in space and time [39], which is why the results of the nuclear methods are considered a relevant estimate of erosive processes in the investigated area.

Table 7. The results of *t*-test

Paired differences			*t*-test	df	Sign. (2-tailed)
95 % confidence interval of the difference					
	Lower	Upper			
Pair 1 EPM – DMM	.3243	2.0690	3.103	9	.013
Pair 2 EPM – PDM1963	–1.2146	1.5858	.300	9	.771
Pair 3 EPM – PDM1986	–5.4851	–.2257	–2.456	9	.036

Table 8. Correlations of selected topographic parameters with model results

	Altitude	Slope	Profile curvature	Planar curvature	NDVI
PDM(1963)	0.11	0.43	–0.45	0.25	–0.04
DMM	0.09	0.39	–0.45	0.29	–0.01
PDM(1986)	0.11	0.43	–0.45	0.25	–0.04
EPM	–0.09	0.15	–0.24	0.13	0.50

CONCLUSIONS

This paper presents a detailed description of the origin and evolution of hanging valley near the geolocation Loess Pyramid, near the Titel settlement, Autonomous Province of Vojvodina, Serbia. The total of 12 soil profiles along the complex gully system and in the vicinity at the edge of TLP, were sampled to investigate erosion and justified further development of these hanging valleys. The method of radiocaesium, and three different conversion models, were used to calculate soil erosion rates. The ^{137}Cs inventory values of each profile were obtained by gamma spectroscopy analysis. Validation of the estimated results was done by comparison with empirical Gavrilović 's model, which is used worldwide in the geographical research of erosion processes.

Based on the linear regression analysis, it can be concluded that the results of Gavrilović 's model are well correlated with the results of the radiocaesium method. The highest value of the Pearson coefficient was obtained for the DMM model ($r = 0.59$), while for PDM (1986) and PDM (1963) a lower correlation coefficient was obtained (of $r = 0.57$), which is expected because this model does not consider subsequent land redistribution. Analysis of some topographic factors (height, slope, profile, and planar curvature) concluded that Gavrilovic's method is more sensitive to the nature of terrain coverage, in contrast to conversion models that showed greater dependence on the slope of the study area. Like similar empirical models (USLE, RUSLE), EPM can only be considered a diagnostic tool that should be combined with other methods. The application of geographic information systems improves the identification and classification of certain parameters necessary for these models.

The general results in all three cases indicate very weak, weak, medium weak to moderate erosion. However, there are some differences that are determined by the character of the chosen method. If we are guided by the fact that no significant radiocaesium deposition has occurred since the dominant fallout radiocaesium in our area (1986) and that its activity concentration in the depth profile of the soil changes relatively slowly, then the method of radiocaesium would be the most realistic in the calculation of erosive processes in the soil. The values of annual soil loss estimated from the values of ^{137}Cs inventory range as follows: for DMM from –1.00 tha^{-1} to –6.00 tha^{-1} , for PDM (1963) from –1.15 tha^{-1} to –6.54 tha^{-1} , for PDM (1986) from –2 tha^{-1} to –16.13 tha^{-1} and from EPM yield 2.86 to 5.82 tha^{-1}.

The last point sampled on the alluvial plain in the case of the ^{137}Cs method showed erosion despite the expected accumulation. By analyzing the water level of the Tisza River from 1986 to 2017, it was found that the water on several occasions led to leaching and removal of ^{137}Cs from the plain into the Tisza riverbed from where it was probably carried downstream to the mouth of the Danube, which would be the subject of some future research. The evolution of valleys along the entire east-southeastern part of TLP can be inferred in a way that they do not have a typical zone of accumulation, so it could be sought somewhere in the western and northern parts of the plateau.

Results of correlation analysis of four topographic parameters (slope, profile curvature, planar curvature and NDVI), and results from four models of conversion, showed that the slope gave the best correlation with radiocaesium conversion models for undisturbed soils, while NDVI gave the best correlation with the results obtained by Gavrilovic's model.

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AUTHORS' CONTRIBUTIONS

The manuscript was written and conceptualized by K. S. Kalkan. Gama-spectroscopy analysis with discussion and validation of data were obtained by S. M. Forkapić, D. S. Mrdja and K. I. Bikit. Statistical analysis and soil erosion modeling was carried out by K. S. Kalkan, S. M. Forkapić, R. S. Tošić, and N. M. Milentijević. S. B. Marković gave an explanation about genesis and evolution of hanging valleys on Titel Loess Plateau. All authors analyzed and discussed the results and reviewed the manuscript.

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ПРОУЧАВАЊЕ ВИСЕЋЕ ДОЛИНЕ У ЛЕСНО-ПАЛЕОЗЕМЉИШНИМ СЕДИМЕНТИМА И ПРОРАЧУН ЕРОЗИЈЕ ЗЕМЉИШТА ПРИМЕНОМ НУКЛЕАРНОГ МОДЕЛА И МОДЕЛА ПОТЕНЦИЈАЛА ЕРОЗИЈЕ

Рад се бави прорачуном годишње ерозивне стопе земљишта коршћењем два различита модела: нуклерног модела и методе потенцијала ерозије, познате као Гавриловићева метода. За подручје истраживања одабран је комплексан систем долина на Тителском лесном платоу. Радиоцезијум је фаворизован у многим студијама као оптимални ерозивни трагач због свог релативно дугог периода полураспада, занемарљивог обнављаља у животној средини и способности снажног везивања за честице земљишта. Употреба гама-спектрометрије у лабораторијским условима за испитивање радиоактивности животне средине представља прецизну и брзу технику мерења за одређивање концентрације активности ^{137}Cs, без потребе за компликованом припремом узорака. Годишње стопе ерозије и акумулације су процењене применом три модела конверзије за необрађено земљиште: модел дистрибуције профила за две године доминантне депозиције радиоцезијума (1963. године и 1986. године) и модели дифузије и миграције за чије потребе је коришћен Walingov програм. Примењени нуклеарни модели су потврђени методом потенцијала ерозије који је најрелевантнији емпиријски модел за ерозивне процесе у бујичним долинама. Добијени резултати указују на добро слагање са углавном ниским вредностима просечних годишњих стопа ерозије земљишта на свим профилима земљишта на истраживаном подручју. Корелационом анализом утврђен је различит утицај нагиба, закривљености терена и вегетационог индекса.

Кључне речи: висећа долина, ерозија земљишта, радиоцезијум, гама-спектрометрија, Гавриловићев метод, Тителски лесни плато