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Applicability of the Gavrilović method in erosion calculation using spatial data manipulation techniques

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Abstract The Gavrilović method has been widely used for the prediction of soil erosion and sediment yield on the basin scale in Slovenia and Croatia in the last 30 years. The method has been developed for management practices in erosion protection, mainly in forest management and torrent control. The Gavrilović method involves a parametric distributed model, and is used for predicting annual soil erosion rates and annual sediment yield. It uses empirical coefficients (erodibility coefficient, protection coefficient, erosion coefficient) and a matrix of physical characteristics of basin sub units. To evaluate its applicability we analysed erosional processes in two neighbouring drainage basins, the Dragonja River basin in Slovenia and the Botonega River basin in Croatia. The results of this study show that GIS techniques can be successfully incorporated into the Gavrilović method.

Key words erosion; sediment yield; Dragonja River; Botonega River; Gavrilović

INTRODUCTION

Erosion control is one of the biggest concerns in integrated water management. Soil erosion is a natural process, but it can be accelerated by certain human activities. Agriculture, where soil loss also represents a loss in nutrients and productive capability, construction, and mining are the most important (Hahn *et al.*, 1994). In the first place, soil erosion causes land degradation, but excessive sedimentation resulting from it can also have an impact on river morphology. Another common problem is the pollutants, eroded and transported alongside with the soil particles. If they are deposited in a marine environment, they can cause serious pollution problems (Horvat *et al.*, 1998). To propose erosion control and stream regulation measures in a watershed, managers should have an understanding of the processes of soil detachment, transport and deposition. Knowing trends of those processes is equally important. Science has always tried to offer practical methods for the evaluation of erosional processes for managerial purposes. The first empirical soil erosion models were proposed by Cook (1936), Zingg (1940) and Smith (1941). As quoted in Gavrilović (1972), in the late 1940s and early 1950s, methods for analysing the severity of erosion were developed. Poljakov (1953) proposed an analytical expression with two parameters, average annual water turbidity and slope of the basin, to determine the erosion development coefficient. As these parameters should be regularly measured in the field, this method has not been widely used. Herheulidze (1947) proposed four categories for the *state of* *torrent development* to describe the degree of erosion in drainage basins with debris torrents. For this categorization, data on slope and some geological parameters of deposited material, are needed. At the same time, Browning (1947) proposed a *relative erosion factor* (Re) as a measure of soil loss due to water erosion. Silvestrov (1955) proposed an analytical equation for the determination of an 'erosion coefficient' (E) for the analysed area. In this equation, some parameters relating to land use and relief are needed. On the basis of the described theoretical work, Gavrilović (1962, 1970, 1972) developed a method for the analytical determination of erosion coefficients and the quantification of erosion and average annual sediment yield. Using field investigations on the Morava River (Serbia), and laboratory experimental work, Gavrilović (1976) prepared detailed tables for the determination of parameters. This method has been widely used in Slovenia and Croatia in the last 30 years to predict erosional processes and implement torrent regulation and other erosion control works.

In this paper, we evaluate the applicability of the Gavrilović method for analysing erosional processes in two sub-Mediterranean basins: the Dragonja River basin in Slovenia and the Botonega River basin in Croatia. Since an array of empirical coefficients based on the physical characteristics of the basin is used in the method, we describe GIS techniques for data preparation and modelling.

METHODS

Gavrilović (1962, 1970, 1972) proposed an analytical equation for determining the annual volume of detached soil due to surface erosion:

$$Wp = \pi * P * F_w * K_t * \sqrt{K_z^{\,3}} \qquad (1)$$

where P is the average yearly precipitation (mm), F_w is the drainage area (km^2), K_t is the temperature coefficient, and K_z is the erosion coefficient. The equation for K_t is as follows:

$$K_t = \sqrt{(0.1 + T/10)} \qquad (2)$$

where T is the average yearly temperature (°C). The erosion coefficient K_z can be estimated using corresponding tables or calculated from:

$$K_z = K_y * K_x * (K_o + \sqrt{F_{sl}}) \qquad (3)$$

where F_{sl} is the average slope of the basin (%), K_y is the soil erodibility coefficient, K_x is the soil protection coefficient and K_o the erosion and stream network development coefficient. Gavrilović suggested calculating the average slope as the total contour line length in the analysed basin multiplied by the contour interval divided by the drainage area. If a digital elevation model is available, the average slope is simply calculated as the average slope of the cells in the basin. When the drainage basin is not uniform with respect to the erosion coefficients, Gavrilović suggested that the basin should be divided into smaller sub areas (hydrographic units). After the annual soil erosion rates Wp are calculated for each hydrographic unit, they are summed to obtain the soil erosion rate for the whole basin.

Gavrilović (1976) has suggested the following equation for determination of the sediment delivery ratio:

$$R_u = \frac{(O*D)^{0.5}}{0.25*(L+10)} \quad (4)$$

where O represents the perimeter of the basin (or sub unit) (km), D is the average height distance of the basin (or sub unit), expressed in (km), and L length of the basin (km). Average height distance is calculated as:

$$D = \frac{\sum_{i=1}^{n} f_i * h_i}{F_w} - H_{\min} \text{ (m)} \quad (5)$$

where f_i represents area between two contour lines (km^2), h_i average altitude between the contour lines (m), and H_{min} the minimal altitude of the basin (m). The actual sediment yield is then calculated as:

$$G_y = R_u * W_s \text{ (m}^3\text{ year}^{-1}\text{)} \quad (6)$$

DESCRIPTION OF THE RESEARCH AREA

The research basins are located on the Istria peninsula along the North Adriatic Sea (Fig. 1). The Dragonja River basin has an area of 91 km^2; the river is 29 km long and flows from east to west. The river at its lower section forms the state border between Slovenia and Croatia, and much of its drainage basin lies in Slovenia. The Botonega River is 24 km long, and has a 98-km^2 drainage area, 73 km^2 of which drains into the

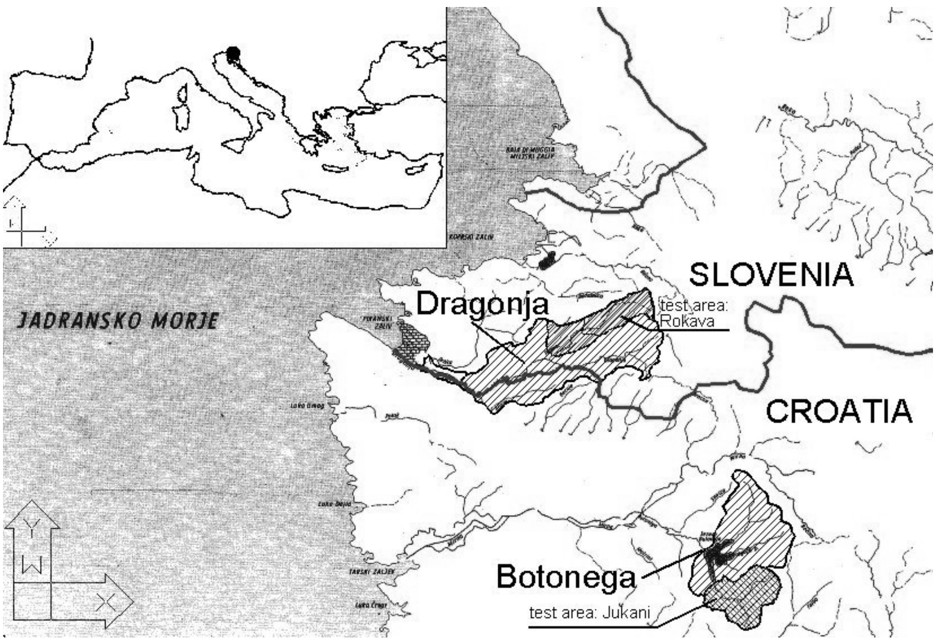

Fig. 1 Map of the research area, showing the Dragonja and Botonega River basins.

Botonega Reservoir. It is a tributary of the Mirna River, which is one of the main rivers in the Istria Peninsula in Croatia. The bedrock in both basins consists of flysch substratum, impermeable and easily erodible, being composed of sandstone and marlstone with some limestone. The climate is sub-Mediterranean with dry, warm summers and wet winters. The annual precipitation of the area is 900 mm near the coast (west) and 1200 mm in the inland portions of the peninsula. The daily maximum rainfall in the area is 175 mm. The annual average temperature is 12°C, with a summer and winter average of 21 and 4°C, respectively.

DATA PREPARATION AND GIS MANIPULATION TECHNIQUES

A study of erosion processes using the Garilović method was undertaken in the Dragonja River basin in 1971. An evaluation of the average annual sediment yield in 1971 was performed for sub-basin units. On the basis of this study, erosion control measures have been applied in the basin since the mid 1970s. After abandonment of agricultural land and subsequent natural reforestation during the period 1975–1995, the extent of forest cover increased from 25% to 65% over this period (Globevnik *et al.*, 1998; Globevnik, 2001). To compare changes in erosion between 1971 and 1995, the same approach as used in the 1971 study was applied. In Fig. 2, the Dragonja River basin is shown with the sub areas (units) used for the calculations in the 1971 study.

To analyse the suitability of the Gavrilović method for use with GIS techniques, we prepared cartographic data on geology, pedology and land use in digital form. Geological maps with a scale of 1:100 000 have been digitized and prepared in AutoCad for the Dragonja River basin and in ArcView for the Botonega River basin. The same was done for pedology maps, which are available at a scale of 1:25 000. The Corine Land Cover Data (European Environmental Agency, 1999) have been used to determine K_x coefficients for both basins. For the upper part of the Dragonja River basin (NE part, Rokava area), the Corine Land Cover map (source: http://nfp-si.eionet.eu.int/ewnsi/index.htm), representing the situation in 1995, and pedology are shown in Fig. 2. The corresponding K_y and K_x coefficients, derived from data on pedology and land cover data, are given in Table 1.

The applicability of the Gavrilović method in the AutoCad Map GIS environment has been tested in the 20.4 km^2 Rokava sub-basin (Fig. 1), which is part of the

Table 1 Values for soil erodibility coefficient, K_y and soil protection coefficient, K_x.

Selected pedological units	K_y	Selected Corine land cover classes	K_x
Carbonatic rendzina on flysch	1.2	1—artificial surfaces; 5.1—inland water	0
Eutric brown soil on flysch	0.9	3.1.1—broad-leaved forest; 3.1.3—mixed forest	0.05
Eutric brown soil on flysch, pseudogleic	1.1	2.4— heterogeneous agricultural areas	0.4
Eutric brown soil, colluvial, on flysch	0.2	3.2.4—transitional woodland shrub	0.5
Fluvisol on carbonatic alluvium	0.2	2.3.1—pastures; 3.2.1—natural grassland	0.6
		2.2—permanent crops	0.7
		2.1—arable land	0.9
		3.3.2—bare rocks; 3.3.6—areas under erosion	0.95

Dragonja River basin. The thematic layers, representing coefficients K_o, K_y and K_x, were overlayed and average slopes for each new polygon were determined. For this purpose we imported Slovene digital elevation data (raster 25 m × 25 m) into terrain modelling software (Quicksurf) and determined the average slope for each polygon on the Rokava basin. A similar procedure was used in ArcView for the Botonega basin. The slope was calculated from the Croatian digital elevation data in the grid of 50 m × 50 m, using the terrain modelling software package Spatial Analyser.

RESULTS

Erosion rates for the Dragonja basin as calculated for 1971 and 1995 in the traditional way are given in Table 2 (Globevnik, 2001). Rates were calculated for 29 hydrographic sub areas (flow direction considered), using one value of each parameter for one sub area. For 1971, specific rates per unit area varied between 200 and 550 m^3 km^{-2}, with the average being 325 m^3 km^{-2}. For 1995, rates varied between 30 and 310 m^3 km^{-2}, with an average rate of 130 m^3 km^{-2}. The result of the overlay analysis of Corine land cover and pedological data for the 20.4 km^2 large Rokava sub-basin (Fig. 3) is 74 polygons. The sum of erosion rates for the Rokava sub-basin, calculated using automatically-derived Gavrilović coefficients, is 1213m^3 $year^{-1}$ (Table 3). The average erosion rate is marginally lower when calculated with spatially distributed parameters

Table 2 Erosion rates in 1971 and 1995 for the Dragonja River basin (for units, Fig. 2).

Units	*F* (km^2)	F_{sl} (%)	*P* (mm)	*T* (°C)	*Kt*	*Ky*	*Kx* 1971	*Kx* 1995	*Ko* 1971	*Ko* 1995	*Kz* 1971	*Kz* 1995	*Wp* (m^3 $year^{-1}$) 1971	*Wp* (m^3 $year^{-1}$) 1995
Sum of units 1 to 12:													9945	3515
13	13.4	23.7	1000	12	1.14	0.64	0.35	0.2	0.2	0.12	0.154	0.078	2895	1039
18	0.66	37.5	1000	12	1.14	0.6	0.35	0.2	0.2	0.12	0.171	0.088	166	62
Rokava (sum of units 13 to 18):													4690	1597
Sum of units 19 to 29													13 534	5990
Sum of all units (F = 86.8 km^2)													28 168	11 102

Table 3 Examples of erosion rate calculation with automatically derived Gavrilović coefficients for the Rokava and Jukani test areas and sediment yield for the Jukani.

	F (km^2)	*P* (mm)	T (°C)	*Kt*	K_y	K_x	K_o	*Kz*	*Wp* (m^3 $year^{-1}$)	*O* (km)	*L* (km)	*D* (km)	*Ru*	*G* (m^3 $year^{-1}$)
Calculation for units on the Rokava test area (Slovenia, on the Dragonja basin), Fig. 3:														
251	0.18	1000	12	1.14	0.1	0.05	0.12	0.002	0.1					
309	0.26	1000	12	1.14	0.6	0.4	0.12	0.138	47.2					
Tot	20.4								1213					
Calculation for units on the Jukani test area (Croatia, on the Botonega basin), Fig. 4:														
J1	3.33	1043	12.5	1.16				0.36	2736	8.8	2.36	0.19	0.4	1130
J7	1.71	1043	12.5	1.16				0.50	2300	5.77	1.29	0.10	0.26	606
Tot	26.7								28 615					10 666

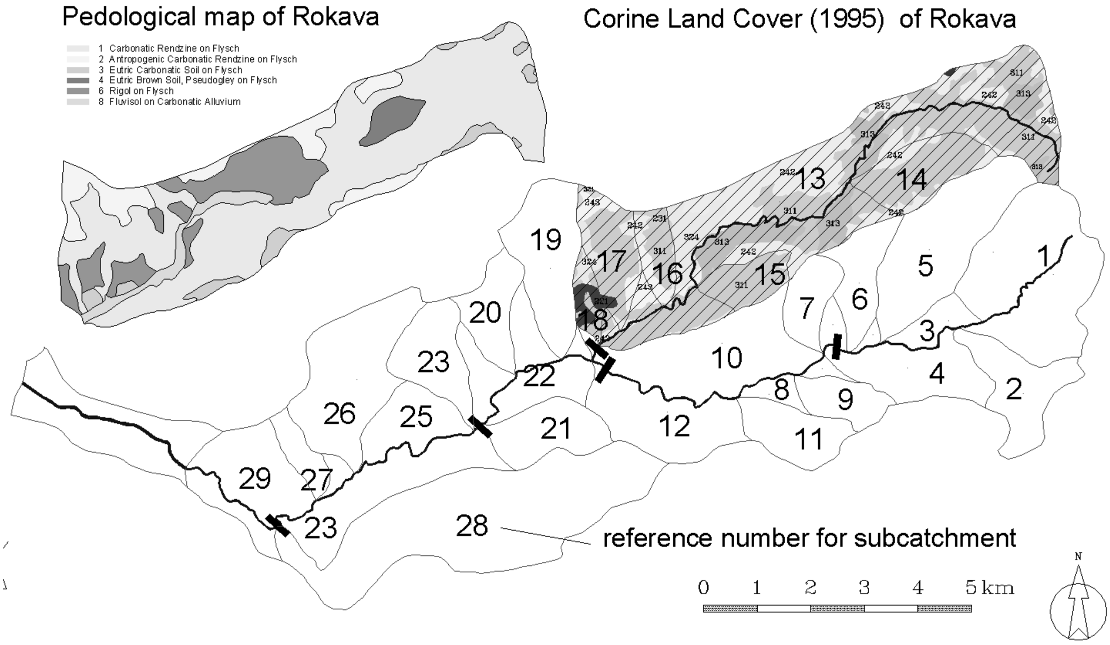

Fig. 2 Pedology, the Corine Land Cover (Table 1) and sub area reference numbers for the Dragonja River basin.

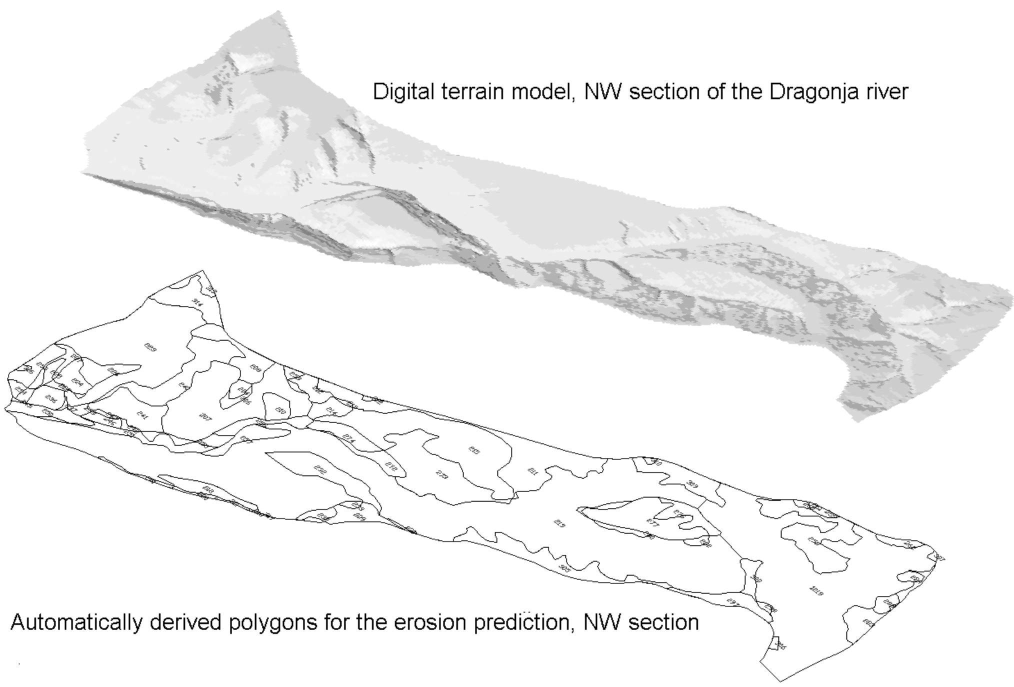

Fig. 3 Digital terrain model and spatial units for the Rokava sub-basin, used for GIS calculation of the Gavrilović coefficients.

and no flow directions are taken into consideration. The annual erosion rate for the Rokava sub-basin calculated with this method was 60 m^3 km^{-2}, whereas it was 78 m^3 km^{-2} if calculated with the traditional method.

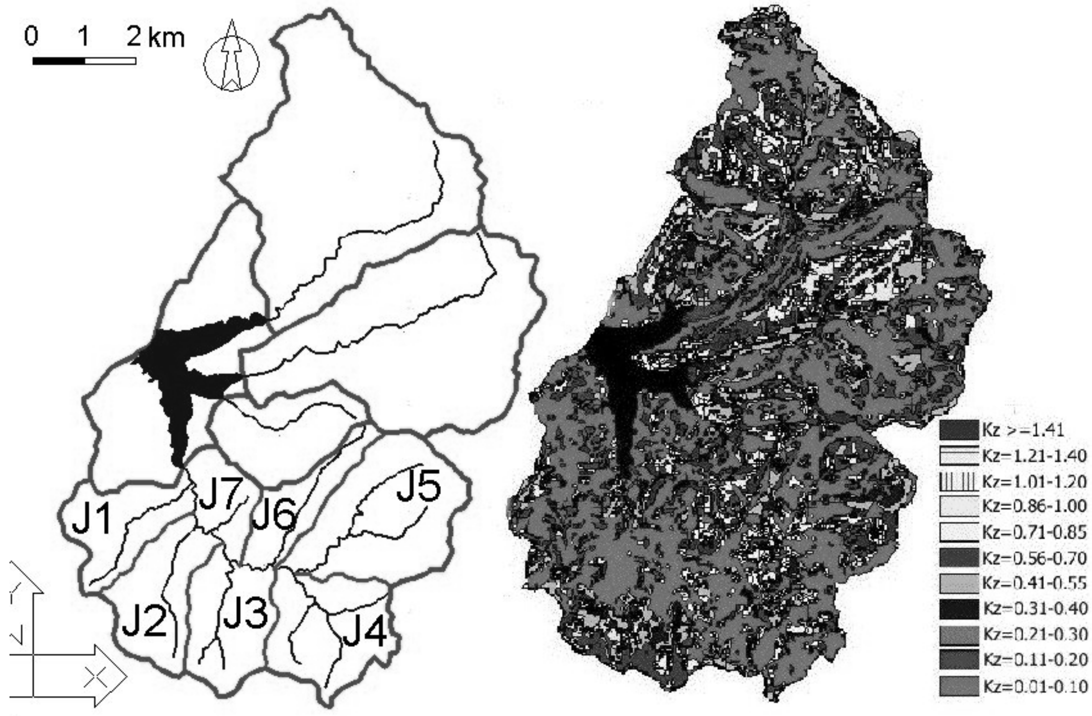

Fig. 4 The Botonega Reservoir basin area with the test area (Jukani), divided into hydrographic units (J1–J7) and results of the erosion coefficient K_z.

In Table 3, erosion rates and sediment yield for hydrographical units in the Jukani test area (on the Botonega Reservoir basin) are presented. The spatially distributed Gavrilović coefficient K_z for the Botonega Reservoir basin as determined with GIS techniques (Holjević, 2002) is presented in Fig. 4. A comparison to the measured value of 19 000 m^3 of deposited material in the period 1989–2000 was also carried out. The computed annual sediment yield of 10 666 m^3 was divided into bed load (1446 m^3) and suspended load (9220 m^3). Based on measurements at high flows and regional experience, the trapping efficiency for suspended sediment was assumed to be 10%. This resulted in a total volume of deposited sediment of 26 000 m^3 in the specified period of 11 years, which can be considered a reasonable agreement between the measured and computed values.

DISCUSSION

Three interesting differences can be observed from the results of this study: the temporal change in soil erosion rates in the Dragonja basins between 1971 and 1995; the remarkable difference in soil erosion rates between two otherwise similar Dragonja and Botonega basins; and finally, the difference in the results when average or distributed values of the parameters are used in the selected hydrographic unit (the Rokava test area).

In 1971, the annual soil erosion rate in the Dragonja basin amounted to 325 $m^3\ km^{-2}$, which is close to the average for the Republic of Slovenia (Mikoš, 1995). In 1995, this figure was reduced by more than half to 128 $m^3\ km^{-2}$. There are two main reasons for this decrease. The first is a conversion of agricultural land to bush and forest land due to the abandonment of previously intensively farmed fields in the area (Globevnik *et al.*, 1998; Globevnik & Sovinc, 1998). In addition, in 1971 systematic erosion control measures were introduced in the area (Globevnik, 1998). Consequently, natural reforestation commenced and, as a result, erosion rates decreased (Globevnik, 2001).

The average annual erosion rate in part of Botonega basin, the Jukani test area, calculated by the Gavrilović method in a GIS environment (Table 4) is 1070 m^3 km^{-2} (Holjević, 2002). This rate is several times higher than the rates in the Dragonja basin or the Rokava sub-basin. The likely reason is the selection of the values of the coefficients, in particular K_o. Another example of extreme erosion in Croatian Istria is the Raša basin (205 km^2) in central Istria, which is similar to the Botonega basin, and has an estimated average annual erosion rate of 1270 m^3 km^{-2}. A detailed survey of the river's estuary between 1938 and 1968 showed that 1 450 000 m^3 of sediment was deposited (Juračić *et al.*, 1995), equivalent to an average annual erosion rate of 230 m^{-3} km^{-2}. Conversely, monitoring of the suspended and bed load in the Rokava sub-basin of the Dragonja basin showed the annual sediment yield of around 50 m^{-3} km^{-2} (Petkovšek, 2002). These data indicate that differences in annual erosion rates between basins can be high, even when they are located close to each other and have similar climatic and geological characteristics.

It is also interesting to observe the difference between the soil erosion rates calculated with the Gavrilović method in a traditional way, using the values of the coefficients for hydrographic units (Table 2), and with distributed values of coefficients for sub units on the basis of land use and pedology (Table 3). The difference between the two approaches on the Rokava sub basin is approximately 20%. For the Jukani basin, Holjević (2002) found that the difference between traditional (58 000 m^3 $year^{-1}$) and GIS methods (28 000 m^3 $year^{-1}$) is even higher. The difference may be explained by the fact that with the GIS approach we delineate the basins into much smaller sub units in the agricultural area, but into larger units in the forested area. The agricultural areas that are prone to more erosion are located on lower slopes, where stream networks are not fully developed, which accord with the lower F_{sl} and K_o coefficients. The forest areas that usually have larger F_{sl} and K_o, have very low K_x (high protection). In the traditional way, the average coefficients of the hydrographic units are used, which do not take into account specific conditions of land use. Within the hydrographic units, frequently the erosion coefficient K_z is not uniform. In this case, its mean value should be calculated. Considering the structure of equation (1), the correct expression for mean K_z is (Petkovšek, 2000):

$$K_z = \left(\frac{\sum K^{1.5}{}_{z,i} \cdot F_i}{\sum F_i} \right)^{2/3} \tag{8}$$

Applying the correct expression for the mean K_z (equation 8) we might get different results.

CONCLUSION

The approaches for using the Gavrilović method in combination with GIS techniques as presented here demonstrate a great potential for soil erosion estimation in basins.

The application of such methods in two similar, sub-Mediterranean basins showed both similarities and differences in the determination of key coefficients between the two different approaches. The main difference was the estimation of the erosion development coefficient K_o, where the severity of erosion is to be assessed. The problem of averaging spatially-variable parameters is also stressed. A possible solution to the latter is the use of homogeneous units that have the same value for all soil-erosion-related parameters. These units can be constructed with GIS techniques, as shown in the given examples.

The Gavrilović method and the presented GIS procedures can be further refined by developing a more representative factor for the impact of precipitation (e.g. R factor from RUSLE equation) and its spatial variability. The Gavrilović method can also be modified in terms of determination of hydrographic units. Gavrilović assumed (Gavrilović, 1972) that the ratio of the perimeter of a hydrographic unit (sub-basin) to its slope length is equal to π (3.14). However, using GIS tools, the ratio can be calculated from the geometric properties of a subunit as derived from pedological and land use characteristics. Following Gavrilović's proposals, the subunit for which coefficients are determined should be a hydrographic unit (sub-basin with developed hydrographic network). How those two approaches interact should be further analysed. In this respect, we should also take into account lateral and riverbed erosion. For further method validation, measurements on both basins have already commenced to monitor actual sediment yield.

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