APPLIED COMPARISON OF THE EROSION MODELS RUSLE-3D, SP AND USPED

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ABSTRACT

Predicting spatial patterns and intensity of soil erosion can be problematic mostly due to few obtainable data. On the other hand, due to GIS platforms, distributed erosion models have evolved and are now commonly used as the georeferenced backbone for the analysis of erosion phenomena. However, the accuracy of their predictions can be seriously hampered by the natural complexity and spatial heterogeneity of the processes acting on the landscape itself. Research on soil erosion modeling is required to get more quantitative information needed to predict potential soil loss and to design and select proper management solutions. Therefore, this paper aims to use and compare three existing low data demanding approaches in combination with different geo-information techniques for analyzing erosion. Three models were selected (RUSLE-3, SP, and USPED) and applied in the upper and the middle sectors of Prahova River Valley. The "predictive power" of the result maps ware tested by analyzing their success rates, which has been obtained by considering the superficial landslides areas as the training set. The implemented models produced realistic estimates. However, model performance was categorized in increasing order as follows: SPL<USPED<RUSLE3D.

Keywords: Erosion modeling, RUSLE-3D, SP, USPED, Success rate

INTRODUCTION

Erosion models represent one of the key aids for forecasting and evaluate soil loss phenomena. Using complex prediction models that require more meteorological, soil or hydrological data than are available is useless and may lead to misinterpretation and erroneous conclusions (Saavedra, 2005). Thus, the prediction should generally be carried out by applying empirical or conceptual approaches. Therefore, there is a continued need to research for models that require minimal input data and to evaluate their ability to represent with sufficient accuracy soil erosion distribution.

This study was undertaken to further improve the knowledge about soil erosion processes in the study area and to better establish conceptual based models as an additional tool in erosion science in Romania. Three conceptual model approaches were selected and used: RUSLE-3D, USPED, SPL. Conceptual models represent a compromise between intensive data demanding (physically based) models and simple-structure regression (empirical models) (Saavedra, 2012).

Two major specific objectives were addressed:

(i) To analyze and review existing soil erosion modelling approaches and select the most applicable ones.

(ii) To give an in-depth insight into the performance of the selected models.

METHODS

1. Study area

The study area overlaps the upper and middle sectors of the Prahova River Valley, located in central-eastern of the country. With the river headwaters in the Clabucetele Predealului Mountains, at an altitude of 1100 m, the Prahova River makes its way between the Bucegi and the Baiului Mountains, representing the geographical limit between the Southern and the Eastern Carpathians. Then it continues its course through the Curvature Subcarpathians with a general NNV- SSE direction of flow. The region of interest covers 56 km along the river. The upper and the middle sectors of Prahova River Valley are an important socio-economic, heavily affected by erosion processes related to the growing demand of an expanding population.

2. Database

All data used for this regional assessment were collected from public data servers (space agencies, international organizations, or research institutions). The inventory map of landslides was based on field surveys supported by the Romanian Space Agency (ROSA) through The Research, Development and Innovation STAR Programme - Space Technology and Advanced Research, funding the research project GEOVIEW, No. 146/2016, having prof. Armaș as principal investigator.

3 Models

3.1 RUSLE-3D

The universal soil equation, under the form of either USLE or RUSLE, is a soil erosion model widely used, from local and regional scales to national (Panagos et al. 2015) and even continental scales (Van der Knijff et al. 2000; Grimm et al. 2002). RUSLE is not an event responsive model, providing only an estimation of soil loss from hillslopes. The RUSLE model is designed to predict only rill and inter-rill erosion. Sediment deposition processes or concentrated overland flow erosion are not taken into consideration (Bosco et al., 2015). The RUSLE equation reads:

$$E_{(r)} = R \times K \times LS_{(r)} \times C \times P \;\; (Eq.1)$$

Where $E_{(r)}$[ton ha^{-1}] is the annual average soil loss; R *[MJ mm ha^{-1} hr^{-1}]* is the rainfall intensity factor; K [ton ha^{-1} per unit R]; is the soil erodibility factor, $LS_{(r)}$ [dimensionless] is the topographical (length-slope) factor; C [dimensionless] is the land cover factor, and P [dimensionless] is the soil conservation or prevention practices factor.

Slope length represents the plan projection of the distance from runoff formation to runoff concentration or the beginning of sediment deposition. Wischmeier and Smith (1978) defined the slope length (L) as “the distance from the point of origin of the surface flow to the point where each slope gradient (S) decreases enough for the beginning of deposition or when the flow comes to concentrate in a defined channel”. The LS-factor is dimensionless, having values that exceed or equal to 0. To incorporate the impact of flow convergence, Mitasova et al. (1998) proposed the replacement of the slope-length factor (L×S) in the RUSLE-3D. The modified LS(r) factor at a point on a hillslope is:

$$LS = (m+1)\left[\frac{A_{(r)}}{22.13}\right]^m \times \left[\frac{\sin\beta_{(r)}}{0.09}\right] \quad (Eq.2)$$

Where $A_{(r)}$ [m^2] is the upslope contributing area per unit of width; $\beta_{(r)}$ [degree] is the steepest slope angle, and *m* and *n* are parameters depending on the type of flow.

In modeling erosion with the RUSLE-3D model, the erosivity factor R [MJ ha^{-1} mm hr^{-1}] quantifies the effect of raindrop impact and reflects the amount and rate of runoff likely to be associated with rain. (Saavedra, 2005). In the current study, the R values were directly imported from the ESDAC database.

The soil erodibility factor K is experimentally determined taking into consideration the soil texture, soil structure, organic matter content, and permeability (Wischmeier and Smith, 1978). Extensive databases of soil samples are not available for the study area, however, the information required for the determination of the K factor at a catchment scale can be derived from soil taxonomy maps obtained from soil reconnaissance survey. For each of the soil textural classes, the mean percentage of silt, clay, and sand can be derived from the texture triangle. In this case and these values can be used to calculate the geometric mean particle diameter D_g [mm] (Shirazi and Boersma, 1984).

$$D_g = \exp\left[\sum_i 0.01 \times f_i \times \ln_{(m_i)}\right] \quad (Eq.3)$$

Where f_i [%] is the particle size fraction and m_i [mm] is the arithmetic mean of the particle size *i*. The K factor can be computed using the equation proposed by Römkens et al. (1986):

$$K = 0.0035 + 0.0388 \times \left[-0.5 \times \left(\frac{\log D_g + 1.519}{0.7854}\right)^2\right] \quad (Eq.4)$$

Cover management factor (C) expresses the erosion protection of vegetation, which is manifested by intercepting falling raindrops, thus reducing runoff. (Patriche, 2012). Following the RUSLE handbook (Renard et al., 1997), the computation of crop management factors is quite complex.

Simplified approaches can be adopted for larger spatial scales: (i) assigning uniform C-factor values found in the literature to a land-cover map (de Vente et al., 2009, Borrelli et al., 2014), or (ii) by deriving the C factor values from satellite images by means of techniques such as image classification (Karydas et al., 2008) and normalized difference vegetation index (NDVI) (Alexandridis et al., 2013). NDVI has proved to correlate poorly with vegetation attributes because of soil reflectance and vitality of vegetation (Vrieling, 2006). Therefore, the crop management factor map was prepared based on the supervised classification method using a Sentinel-2 satellite image.

The effect of contouring and tillage practices on soil erosion is described by the Support practice factor P (Saavedra, 2005). Wischmeier and Smith (1978) define the support practice factor as the ratio of soil loss with a specific support practice to the corresponding soil loss with up-and-down cultivation. Given this scenario, the RUSLE-3D model was run with a P factor of 1, reflecting the desire to predict erosion potential under the conditions of no structural soil conservation support practice.

3.2 USPED

Unit Stream Power Erosion Deposition Model predicts the spatial distribution of erosion, as well as the deposition areas. It uses a dimensionless index of sediment transport capacity $T_{(r)}$ and a topographical index E_d, representing the change in transport capacity in the flow direction, to estimate the spatial distribution of both erosion and deposition (Saavedra, 2005). The parameter $T_{(r)}$ is derived from the unit stream power theory. The upslope contributing area is used as a proxy for water flux at a given location or grid cell. The sediment flow rate $a_{s(r)}$ at the sediment transport capacity $T_{(r)}$, r= (x, y) which is approximated by Julien and Simmons (1985) is described by:

$$\left|q_{s(r)}\right| = T_{(r)} = K_{t(r)} \times \left|q_{(r)}\right|^m \times \ (sin\beta_{(r)})^n \quad (Eq.5)$$

where $\beta_{(r)}$ *[deg]* is slope; $q_{(r)}$ is water flow rate; $K_{t(r)}$ is the transportability coefficient dependent on soil and cover; *m, n* are constants depending on the type of flow and soil properties. For overland flow, the constants are usually set to m=1.6, n=1.3.

Since no experimental work was carried out to develop the parameters needed for Unit Stream Power Erosion Deposition Model, the RUSLE parameters were used instead. The sediment flow at sediment transport capacity can be estimated as (Mitas and Mitasova, 1998):

$$T_{(r)} = \ R \times K \times C \times P \times A^m \times (sin\,\beta_{(r)})^n \quad (Eq.6)$$

where $R \approx i^m$; $K \times C \times P \approx K_{t(r)}$; $LS_{(r)} = A_{(r)}m \times sin\,\beta_{(r)}^n$ *and* m=1.6, n=1.3 for prevailing rill erosion. For prevailing sheet erosion, m=n=1. According to Mitas and Mitasova (1998), the net erosion-deposition E_d is estimated as a change in sediment flow rate expressed by a divergence in sediment flow:

$$E_d = div(T_{(r)} \times s) = \frac{\partial(T_{(r)} \times \cos\alpha)}{\partial x} + \frac{\partial(T_{(r)} \times \sin\alpha)}{\partial y} \quad (Eq.7)$$

Where α [degree] is the aspect of the elevation surface or direction of flow minus gradient direction.

3.3 SPL

The stream power law model for fluvial erosion states that erosion is proportional to the product of river slope and discharge, and therefore has a direct connection with the sediment transport. This relationship has been used to investigate matters from sediment transport at a river cross-section (Bagnold, 1966) to the evolution of long river profiles across mountain ranges over geologic time (Kirby and Whipple, 2001). Because it can be computed remotely without any extensive field measurements, it allows researchers to determine sediment transport inexpensively and quickly. According to Stock and Montgomery (1999), the stream power incision equation can be written as:

$$E = \ K_1 \times A^m \times S^n \quad (Eq.8)$$

where E [m yr-1 per area unit] denotes erosion or denudation rate, K_1 [m^x yr^{-1}] is the erosion coefficient encompassing the effects of lithology, soil and climate, A [km^2] is the upstream drainage area and S [m m^{-1}] is the slope gradient. The soil detachability index was obtained from the literature (Saavedra, 2005).

RESULTS

The soil loss values estimated by each model were grouped into six susceptibility classes. Table 1 relates the erosion intensities obtained by the different models to the percentage area that is affected. It is predicted, that on average, about 70% of the very studied area experiences low erosion, whereas 7.09% of the area faces a medium and medium-low soil loss. The proportion of the area with a very high and extreme intensity of erosion is 7.17% (RUSLE-3D), 4.4% (USPED), and respectively, 12.60% (SLP).

Table 1: Area of different erosion classes

Erosion susceptibility class	Rate of erosion	RUSLE-3D		USPED		SLP	
	[ton ha^{-1}]	[km^2]	%	[km^2]	%	[km^2]	%
Low	0-0.5	258.27	70.33	268.07	73.00	238.69	65.00
Medium-Low	0.5-2	18.21	4.96	33.05	9.00	25.34	6.90
Medium	2-5	26.55	7.23	24.97	6.77	28.28	7.70
High	5-10	37.86	10.31	24.97	6.93	28.64	7.80
Very high	10-50	22.77	6.20	15.42	4.20	35.99	9.80
Extreme	>50	3.56	0.97	0.73	0.20	10.28	2.80
Total		367.22	100	367.22	100	367.22	100

Predicted soil loss rates generated by the three models range from 0.002 to 330 ton ha^{-1} yr^{-1}. The highest average annual estimated erosion rate is provided by the SPL [8.07 ton ha^{-1} yr^{-1}], followed by RUSLE [2.4 ton ha^{-1} yr^{-1}], and the lowest by the USPED [1.2 ton ha^{-1} yr^{-1}] model. Considering the European mean soil loss rate is [0.7 ton^{-1} ha^{-1} yr^{-1}] (Panagos et al., 2015), and 70% of the study area is occupied by forests, we can assume that SPL produced unrealistic values.

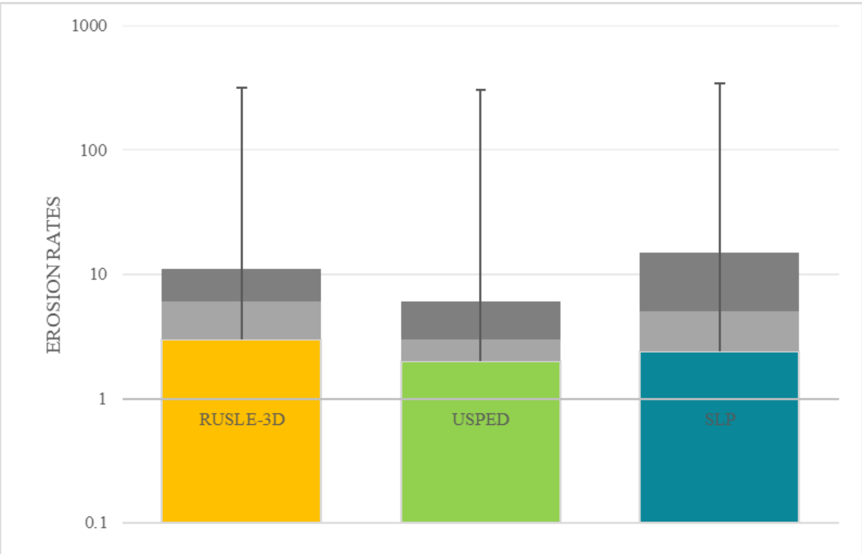

Figure 1 – Box whisker plot of the erosion rates estimated by RUSLE-3D, USPED, SLP

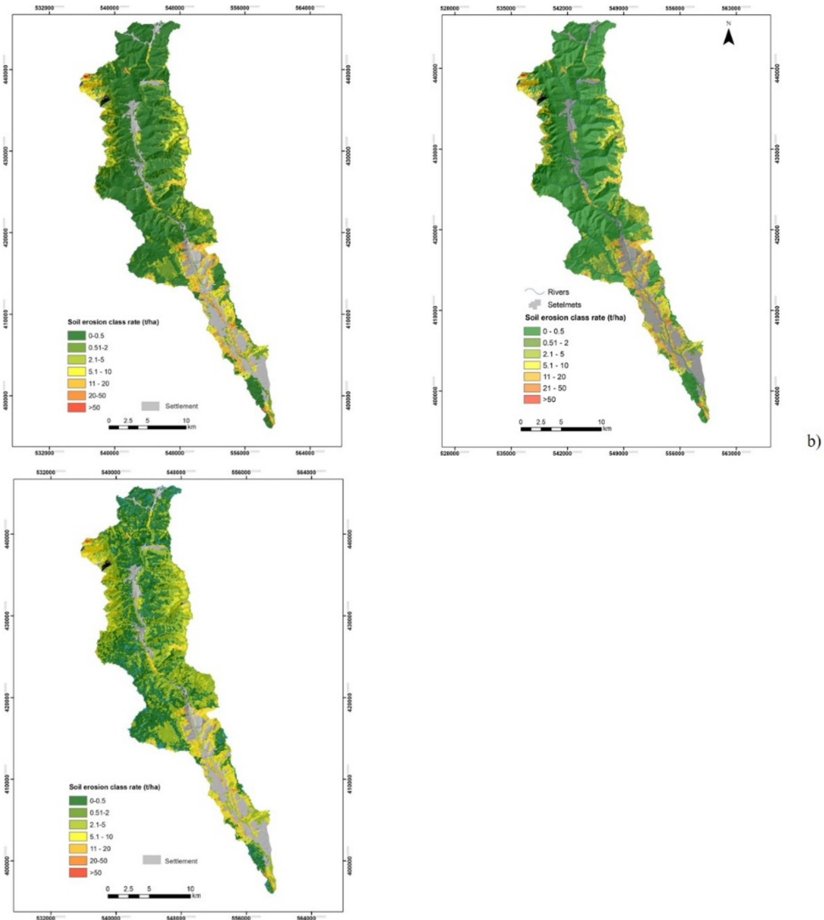

Figure 2 - Erosion map rates: a) RUSLE, b) USPED, c) SPL

The “predictive power” of the output maps can be tested by analysing their success rate. The success rate is calculated by ordering the pixels from high to low values, based on the frequency information from the histogram. After that, an overlay is made with the landslide inventory map (Armaș, 2011), and the joint frequency is calculated.

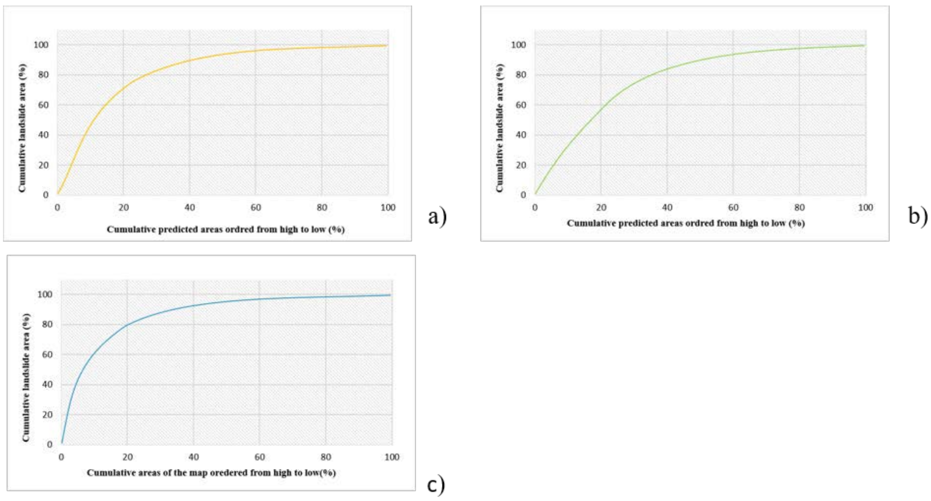

Figure 3 – Success rate graph: a) RUSLE, b) USPED, c) SPL

The success rate indicates how much percentage of all landslides occur in the pixels with the highest values of erosion.The success rates have a very similar shape, the model SLP and RUSLE-3D showing the highest gradient.

CONCLUSIONS

For the present study, three distributed conceptual models were selected based on the reasonableness of the model and the availability of the data. They all allow the prediction of the location of erosion source, as well as the quantity of soil. They predict erosion rates on an annual basis, considering the spatial distribution of the erosional model variables. The differences of the results are significantly influenced by the weights each individual model assigns to the major erosion controlling variables, such as soil properties, land cover, slope gradients, and precipitations. For example, the high values computed by SLP are due to the fact that the model overemphasizes the effect of the channel gradient and the flow accumulation. Thus, the highest erosion rates are predicted only along the major channels and the steep escarpment. The spatial patterns of the USPED model are similar to those of the RUSLE-3D model, showing consistently that the main driving factors for erosion are land cover and relief. The common limitation of the selected models is that no explicit gully erosion or mass wasting procedures are included in the three model approaches used. Although the most up to date geodata was used in this assessment, there are still uncertainties involved in the erosion estimations, which, therefore, increases the importance of validating the results. Fully quantitative validation of erosion rates is hence not feasible for the study area since it is very difficult to acquire soil erosion measurements for catchment areas. While soil erosion rates based on field measurements are not available at the catchment or regional scale, they may be monitored at a plot or field scale. Even so, such data is often not comparable because of non-standardized methodologies and non-uniform experimental conditions. The “success rate” was used to determine the overall reliability of the model predictions. The results showed a satisfactory agreement between the susceptibility maps and the landslide location. Therefore, we can conclude the implemented methodology, based on low model data requirements, produced reliable estimates. Still, errors and uncertainty of the results can be associated with the quality of the input data, not only the model structure itself. Also, the multiple alternatives for substituting certain factors may lead to less accurate outputs. The results can be compared with the ones achieved by the application of other models (*e.g.,* ROMSEM for Romania). Although simulation modeling is a cheap and rapid method of investigation, it cannot replace field data collection and field experiments. Nevertheless, conceptual models are reliable and valuable tolls for predicting soil loss rates.

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