Sheet and Rill Soil Erosion Estimation for Agricultural Land Evaluation

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Abstract. Soil erosion is an important limitative factor concerning agriculture. The estimation of soil erosion is needed for the agricultural land evaluation process, especially in the suitability process, as in Romanian land evaluation methodology. DEMs and thematic layers (geomorphometric parameters, land cover, soil particle-size) were used to apply several soil erosion models: USLE, RUSLE3D and USPED. Geostatistics was used to assess soil erosion modeling results, using soil legacy data. The areas mapped as potentially eroded and according to the strength of the potential can be used to derive a percent of the land mapping unit covered by soil erosion in different grades, according with Romanian land evaluation methodology, but care must be taken to the quality of input data, for obtaining a precise estimate.

Keywords: soil erosion, USLE, RUSLE3D, USPED, land evaluation.

INTRODUCTION

Soil erosion is a limitative factor in agriculture, because diminish soil productivity by physical destruction of fertile soil horizons. Soil erosion by water refers to splash, sheet, rill and gully erosion (Moțoc et. al., 1975, Boardman and Poesen, 2006).


At regional scales, there are several sheet and rill soil erosion models, which are suitable for the estimation of erosion rates for agricultural land evaluation purposes. USLE is an empirical-statistical model, which estimate annual sheet and rill erosion rates on field plots and 7 factors, the rainfall energy being the principal component:

\[ A = R + K + L + S + C + P \]

where, \( A \) = computed soil loss per unit area, \( R \) = rainfall energy factor, \( K \) = soil erodability factor, \( L \) = slope-length factor, \( S \) = slope-steepness factor, \( C \) = cover and management factor, \( P \) = support practice factor. For Romania, USLE was modified by Moțoc et. al., 1979, by specification of the factors for Romania. RUSLE (Renard et. al., 1991, Renard et. al., 1997) is an USLE improvement, by a better specification of the factors.

The limitations of USLE/RUSLE models are clearly showed by Renard et. al., 1991, in that they estimate average annual soil loss by sheet and rill erosion on erosion sites, not depositional (toe of concave slopes), and in general underestimate measured erosion rates (Waren et. al., 2005). USLE and RUSLE were seen only as tools for estimation of soil erosion for farm planning. Despite this, they remain valuable tools for soil erosion estimation on extended areas, because they are very simple to apply, especially in GIS environment. GIS
implementation on DEMs need some modifications, which were done by Mitasova et. al., 1996, Mitasova and Mitas, 1999, Warren et. al., 2005, in the RUSLE3D and USPED (Unit Stream Power Erosion Deposition) models. RUSLE3D is a model derived from USLE/RUSLE by incorporating specific catchment area (SCA) instead of slope length (SL). So, the equation for computing of LS for RUSLE3D became:

$$LS = \left( \frac{SCA}{22.134} \right)^m \left( \frac{\sin S}{0.09} \right)^n$$

(2)

where, $m$ and $n$ are parameters controlling the amount of rill/inter-rill erosion (Moore and Burch, 1986, Mitasova et. al., 1998).

Using the sediment production rates computed with RUSLE3D, as sediment transport capacity (T), the USPED model estimate an erosion/deposition index (EDI), by partial differentiation of the change of T (Mitasova et. al., 1996):

$$EDI = \frac{\delta(T\sin a)}{\delta x} + \frac{\delta(T\sin b)}{\delta y}$$

(3)

where $a =$ exposition. Negative values for the EDI show potential for erosion, while positive values show potential for deposition.

If for a given area with a given DEM we compute RUSLE3D and USPED only concerning LS factor, and considering all other factor with value equal to 1 (K factor may be considered 1.2 for a worse case bare soil condition), we actually model the topographic potential for soil erosion. This estimate is the worst case possible. Starting from this potential, we can apply various scenarios using values for K, C and P factors: actual situation and management scenarios. By using ratios we can also model the sensitivity to specific management practice (Ouyang and Bartholic, 2001).

USLE/RUSLE3D and USPED results as raster grids can be used to determine the surface affected by soil sheet and rill erosion, for every soil mapping unit. For considering a pixel as eroded we must define a soil loess rate threshold. This threshold can be considered the 6 t/ha/years, under which soil rehabilitation by natural processes occur (Moțoc et. al., 1975).

MATERIALS AND METHODS

The study area, soil legacy database and soil covariates are the same used and presented by Tanasă et. al., 2010. The Digital Elevation Model (DEM), was obtained by interpolation from 1:25 000 topographic maps contours and 1:5 000 topographic maps height points. The interpolating algorithm was Multilevel Thin Plate Spline from SAGA GIS (with 11 levels for a smoothing of the DEM surface). The river network extracted from 1:25 000 topographic maps was enforced to the DEM and then further preprocessing for hydrological modeling by filling the sinks, was performed. The pixel size was choose to be 12.5 x 12.5 m, after Hengl et. al., 2004 guidelines.

The RUSLE3D and USPED model were implemented in the GRASS GIS, following the Mitasova et. al. 2000 guidelines.

Rainfall factor (R) for the study area is 0.13 (Moțoc et. al., 1978). Soil erodability factor (K) was obtained by applying RUSLE methodology (Renard et. al., 1997):

$$K = 7.594 \left\{ 0.0034 + 0.0405 \exp \left[ -\frac{1}{2} \left( \frac{\log(Dg) + 1.659}{0.7101} \right)^2 \right] \right\}$$

(3)
where, \( D_g[\text{mm}] = \exp (0.01 \sum f_i \ln m_i) \) (\( D_g \)=geometric mean particle diameter), \( f_i \) = primary particle size fraction in percent and \( m_i \) = arithmetic mean of the particle size limits of that size (for Romania, clay=(0+0.002)/2=0.001, silt=(0.002+0.02)/2=0.011 and sand=(0.02+0.22)/2=0.11s). This formula was applied to regression kriging estimates of clay, silt and sand % values of the soil profiles database described in Tanasă et. al., 2010, obtaining values for K factor between 0.27 and 0.33.

Slope length and slope steepness factor (LS) for the classic USLE was computed using GRASS GIS 6.4.1 after Moțoc et. al., 1978 equation:

\[
LS = L^{0.3} \times (1.36 + 0.97 \times i + 0.138 \times i^2)
\]  

(5)

where, \( L \) = pixel length (12.5 m for N, S, E, W orientations, and 17.68 m for NE, SE, SW, NW orientations) and \( i \) = slope in percents (%).

Slope and aspect were computed using GRASS GIS 6.4.1 r.slope.aspect using a 2FD algorithm (Zhou, 2004) and 3x3 pixels neighborhood, which is suitable for smoothed DEMs. The slope length was computed from DEM in SAGA GIS 2.0.7 using deterministic infinity algorithm of Tarboton, 1997. Specific catchment area was obtained using SAGA GIS 2.0.7 and the flow tracing algorithm DEMON (Costa-Cabral and Burges, 1994), which simulate dispersion. The \( m \) and \( n \) parameters for RUSLE3D were chosen: 1.6 with 1.3 for rill erosion predomination, and 1 with 1 for sheet erosion predomination (Mitasova et. al., 1996). A mean values between the two values was computed for RUSLE3D used in figures and statistical analysis.

Cover factor (C) for the year 2000 was obtained from Landsat ETM+ images (band 1-3, 5 and 7) downscaled to DEM resolution with splines. Lakes, built areas, vineyards and orchards were extracted by interpretation from LANDSAT data. Forests, pastures and agricultural lands were obtained using a cluster analysis applied to the following layers: PCA 1 which describe 0.72% of the variance for the six bands, SAVI (Huete, 1988), Brightness, Greeness and Wetness Kauth Tasseled Cap (derived using values for Landsat ETM+ by Huang et. al., 2002). Bare earths were extracted by cluster analysis from Kauth Tasseled Cap and slope layers. The used values of factor C (Moțoc et. al. 1978) are: agricultural lands 0.5, pastures 0.3, bare earth 1.2, vineyards 0.7, orchards 0.5 and forests 0.001.

Practice factor (P) was only modeled, with 1 value for no anti-erosional practice in the actual land use scenario, and with contour tilling scenario (with different values based on slope class, after Moțoc et. al., 1978). A modeling approach was chosen because the cover factor is dynamic, while rainfall, soil erodability and practice are relative stable. For modeling land cover type, in a management approach we modified the cover of steep hillslopes (with slopes > 20%) with forests.

Statistical analysis and graphics of the results were performed in R statistical software (Ihaka and Gentleman, 2006). For the modeling results of RUSLE3D, built areas, lakes, floodplains and areas with EDI potential deposition were excluded from the analysis.

RESULTS AND DISCUSSION

The results for USLE and RUSLE3D LS factor are presented in Fig. 1, for a selected area, south from Podu Iloaiei city, in Scobâlteni-Răpâgău basin. Sub-figures a, b, c shows the results for the classic USLE, USLE with DEM modeled slope-length and RUSLE3D modeled, only with LS factor, as maximum possible erosion estimate.

All modeling results shows very high maximum erosion rates, values exceeding 200 t/ha/y being unrealistic (Moțoc et. al., 1979 cite values close to 200 t/ha/y for bare lands on control plots, without reference to slope gradient and slope lengths of the parcel, while Cerdan
et. al., 2006 mention for Europe a mean of 23.40 and maximum values of 70 t/ha/y for bare land plots, and Zhang et. al., 2011 mention values close to 350 t/ha/y for cultivated lands with seasonal no cover in 1200 mm mean annual rain monsoon climate of Anhui province, China).

Fig. 1. Spatial results for the USLE and RUSLE3D topographic potential, USPED EDI and management modeling results of soil sheet and rill erosion estimation (for visualization purposes the grey tones are scaled and with logarithmic stretch)

Classic USLE show unrealistic values on high slopes, USLE using slope length show unrealistic values on dip cuesta very long slopes and RUSLE3D show unrealistic values in
area of flow convergence. Using $^{137}$Cs measured soil erosion rates Warren et. al., 2005 showed that RUSLE3D gave better results than USLE with slope length and classic USLE. The analysis of the histograms and box and whisker plots from Fig. 2 and 3 for USLE and RUSLE3D maximum topographic erosion estimate we can say that USLE and RUSLE3D results are the most suitable for erosion estimate, while USLE computed with DEM slope length is unrealistic. Considering erosion values from the literature and the mean annual rain under 600 mm from the study area we assigned a maximum value of 200 t/ha/y for the values exceeding this value in the actual and modeling scenarios of RUSLE3D sheet and rill soil erosion estimation. These very high and unrealistic values appear in areas where flow concentration appear (and slope length and specific catchment area have high values), and erosional EDI values appear.

Sub-figure d show the results only for probable erosion areas, separated as zones with negative values of EDI. These areas are clearly correlated with hillslope toe slopes and areas of flow concentration. Sub-figure e, f, g, h figure the results of RUSLE3D for several modeling situations. Probable deposition areas (with positive EDI values) are masked.

The statistical results of the USLE and RUSLE3D are represented as histograms in Fig. 2 and as box and whisker plots in Fig. 3, for several modeling situations. Tab. 1 depicts the descriptive statistics of the modeling results.

![Fig. 2. Histograms of USLE and RUSLE3D topographic potential and management modeling results of soil sheet and rill erosion estimation](image)

From the study area (969.27 km$^2$), the floodplains (areas of sedimentation), lakes (sinks for water and sediments) and built areas represent 341.83 km$^2$, and were excluded from the analysis. From the remained area, where the erosion could occur, only 344.87 km$^2$ has EDI negative values, which show high potential for soil erosion (sheet and rill), 262.56 km$^2$ showing potential for deposition.

The success of USLE/RUSLE3D approach is based on the quality of factor data (Waren et. al., 2005). Errors related to DEM properties and geomorphometric parameters computation algorithm can be significant if these aspects are ignored. First, it is known that gridded representation of DEMs limits the rise and run slope components, our slope values doesn’t exceed 22.5° (45%). A smaller cell size for the DEM doesn’t necessary resolve this
problem. The slope computation algorithm also influence slope values, algorithms which use bigger neighborhood and polynomials to fit the surface, giving smaller slope values, than maximum gradient algorithms.

The descriptive statistics of USLE and RUSLE3D topographic potential and management modeling results of soil sheet and rill erosion estimation

<table>
<thead>
<tr>
<th></th>
<th>USLE slope length</th>
<th>RUSLE3D actual cover</th>
<th>RUSLE3D contour tilling</th>
<th>RUSLE3D forest on slopes &gt; 20%</th>
<th>RUSLE3D contour tilling + forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>2.91</td>
<td>0.00001</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Q1</td>
<td>23.20</td>
<td>379.70</td>
<td>15.62</td>
<td>0.25</td>
<td>0.16</td>
</tr>
<tr>
<td>Median</td>
<td>53.42</td>
<td>938.40</td>
<td>53.86</td>
<td>0.96</td>
<td>0.69</td>
</tr>
<tr>
<td>Mean</td>
<td>70.53</td>
<td>1436.00</td>
<td>4615.00</td>
<td>3.19</td>
<td>2.60</td>
</tr>
<tr>
<td>Q3</td>
<td>102.01</td>
<td>1913.00</td>
<td>136.6</td>
<td>2.61</td>
<td>2.01</td>
</tr>
<tr>
<td>Max.</td>
<td>764.55</td>
<td>28720</td>
<td>1298*10^6</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>

Note: Column 2-4 describes the whole grid results, while columns 5-8 describes masked grid for lakes, build and erosion EDI areas.

For Romanian implementation of USLE (Moțoc et. al., 1979) soil erodability factor have values between 0.6 and 1.2, chernozems having values down to 0.6, while RUSLE formula (eq. 3) gave us values between 0.27 and 0.33. While Romanian implementation gave a table from which we choose the values according to soil classification, RUSLE methodology has a statistical sounding formula. The choose of one or other method can influence the final results.

Geostatistics applied to soil legacy database and soil covariates can model first soil horizon depth (Niculiță et. al., 2010, Tanasă et. al., 2010), which can be used further to assess USLE/RUSLE3D/USPED success. Also mapped eroded soil can be used in this approach, but care must be taken because soil erosion is strongly influenced by agricultural practices, USLE defining only the “feature” space were erosion can occur, and not the actual points of erosion presence. For the last approach, physical erosion models (WEPP) can be used. Using 288 measured A horizon depths, Niculiță et. al., 2010 derived a regression kriging modeling with a significant 0.12 R^2 coefficient and a 14.04 cm std. dev. and 0 cm mean of residuals (which
show a normal distribution). Considering the values smaller than 14.04 cm A horizon depth as eroded soils a good agreement is obtained comparing with EDI potential erosion areas. From the 620 soil profiles of Niculîță et al., 2010 and Tanasă et al., 2010, EDI depositional areas include 23 soil profiles with coluvic subtype (while only 2 in erosional areas), and from 35 erodosols and regosols, 40% are contained in erosional EDI areas, with a mean soil erosion estimation of 6.8 t/ha/y.

CONCLUSIONS

The present study shows how DEMs, geomorphometric parameters and soil erosion models can be used to assess soil erosion potential. The areas mapped as potentially eroded and according to the strength of the potential can be used to derive a percent of the land mapping unit covered by soil erosion in different grades, according with romanian land evaluation methodology (I.S.S.A., 1978, I.S.S.A., 1987a, I.S.S.A., 1987b, I.S.S.A., 1987c). Care must be taken to the quality of input data, for obtaining a precise estimate.

Acknowledgments. This work was supported by the European Social Fund in Romania, under the responsibility of the managing Authority for the Sectoral Operational Programme for Human Resources Development 2007-2013 [grant POSDRU/88/1.5/S/47646].

REFERENCES


