Ideas for Physical Interpretation of the USLE

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Soil erosion by water – extend, processes and modelling for conservation planning.

In order to develop sustainable systems of agriculture that satisfy the present and the future needs of the mankind, there must be reliable information on the constrains and potential of the land resource. The UNEP Project GLASOD (GLobal Assessment of SOil Degradation) recognized erosion by water as the most important soil degradation type, representing more than a half of all soil degradation.

Soil erosion by water refers to a series of processes leading to soil depletion and export of sediment. It takes place through three main processes: (i) mechanical disruption, slaking, compaction, dispersion and detachment of soil particles, aggregates and clods from the soil mass due to the impact of raindrops and the overland flow; (ii) movement of detached material by gravity or by overland flow and (iii) deposition.

Planning for soil and water conservation measures requires knowledge of the relations between the driving forces that cause loss of soil (e.g. the erosivity of rainfall, the slope of the land, the erodibility of soil) and the factors that help to reduce such loss (e.g. the plant cover, the conservation practices and measures, the soil resistance). The first developed and one of the most widely-used models for effective conservation planning based on predictions of average annual soil erosion rates and able to estimate soil loss over a wide range of situations is the Universal Soil Loss Equation (USLE). The USLE approach to soil erosion description is empirical and based on statistical relationships undermining its universal applicability. Further I will discuss ideas for introducing deterministic elements in the USLE approach for estimating the cover and management factor (C) and the soil erodibility factor (K).

Cover and management factor (C)

Concepts. Vegetation, being the most important component of the earth's ecosystems, modifies the impact of raindrops and overland flow. Vegetative canopy influences soil and water losses by changing the impact and intensity of rainfall, the resistance to water flow through the enlarged by plants hydraulic roughness, the total amount of water available to transport sediment and the distribution of throughfall. It has been known at least since 1916 that plants intercept and transmit rainwater down their stems and at least since 1948 that vegetation canopies change the drop-size distribution of rain and that splash detachment under canopies is different from that on a bare soil. For the time being, it has been known that vegetation affects the rainfall impact on soil through storing rainwater on leaves and branches (intercepted store), transmission of rainwater down the leaves, branches and stems to the ground (steam flow) and transformation of the rainwater to water drops drained from the leaves (leaf drainage).

Considering the present state of knowledge about the role of vegetation during rainfall event, the net volume of the rainfall (*NR*) at any moment (*t*) after the start of rain can be conceptually presented as a sum of four portions: (i) rainfall directly reaching the soil (*DR*); (ii) rainwater intercepted by the vegetation (*IR*); (iii) rainwater reaching the ground through flow down the leaves and stems (*SF*) and (iv) rainwater reaching the ground as modified by the vegetation rainfall (*MR*):

(1) $NR(t) = DR(t) + IR(t) + SF(t) + MR(t)$.

With respect to soil erosion, *IR* and *SF* do not directly contribute to soil detachment. Hence, the net rainfall impact energy on soil with vegetation cover (KE_{imp}) should be considered for *DR* and *MR*:

(2) $KE_{imp}(t) = KE_{DR}(t) + KE_{MR}(t)$.

To resolve equation (2), we should take into account the following relationships.

- $DR(t)$ is proportional to $NR(t)$ with coefficient of proportionality equal to the portion of the soil that is not protected by the vegetation canopy:

(3) $DR(t) = (1\text{-}c)\ NR(t)$;

- the model of Van Elewijck, modified by Morgan et al. for the stemflow is:

(4) $SF(t) = 0.5\ (TIF) \cos \alpha$;

- the sum of $IR(t)$ and $SF(t)$ is actually the temporary intercepted by vegetation rainfall (*TIF*):

(5) $TIF(t) = IR(t) + SF(t)$;

- the model of Merriam (1973) for the interception store is:

(6) $IR(t) = IR_{max}\ \{1 - \exp[- DR(t)/IR_{max}]\}$.

Substituting equations (3), (4), (5) and (6) in equation (1), resolving it for MR(t) and taking into account that

(7) $EK_{MR}(t) = 0.5\ V^2\ MR(t)$,

(8) $KE_{DR}(t) = (1\text{-}c)\ KE_{rain}(t)$,

we obtain an equation for estimating the impact energy of rainfall on soil with vegetation cover at any moment (*t*) after the start of rain:

$$(9)\ EK_{\text{imp}}(t)=(1-c)EK_{\text{rain}}(t)+0.5(1-0.5\cos\alpha)V^2\int_0^t\{cDR(t')-IR_{\max}\{1-\exp[-DR(t')/IR_{\max}]\}\}dt',$$

where: $EK_{\text{imp}}(t)$ is the impact energy of rainfall on soil with vegetation cover, J $m^{-2}mm^{-1}$; $EK_{\text{rain}}(t)$ is the impact energy of rainfall on bare soil, J $m^{-2}mm^{-1}$; c is the canopy cover, expressed as a portion of the ground area covered by vegetation canopy ($1 \geq c \geq 0$); α is the average acute angle (degrees) of leaves and branches to the plant stem; V is the fall velocity of the drops dripping from the vegetation on the soil, m s^{-1}; DR is the volume of rainfall, mm; $IR_{\max}$ is the maximum volume, mm, of the interception store for particular crop or vegetation cover.

The concept of the USLE cover and management factor(C) can be presented as:

$$(10)\qquad C=\sum_{k=1}^{7}(EI_{30}\sum_{j=1}^{m}\ \sum_{i=1}^{n}\frac{A_{\text{C}ijk}}{A_{ijk}})$$

$$(11)\qquad C\propto\frac{A_{\text{C}}}{\text{A}}=F_{\text{C}}\frac{EK_{\text{Cimp}}}{EK_{\text{Rimp}}}\quad,$$

where: A and EK_{Rimp} are the soil loss and the rainfall impacting energy for bare soil; Ac and EK_{Cimp} are the soil loss and the rainfall impacting energy for a specific vegetation; EI_{30} is the rainfall erosivity factor; F_{C} is a constant characterizing the specific vegetation.

Equation (9) can be written as:

$$(12)\qquad \frac{EK_{\text{C imp}}}{EK_{\text{R imp}}}=1-c+\frac{0.5V^2n(1-0.5\cos\alpha)(cP-IR_{\max})}{EK_{\text{rain}}},$$

Substitution of Equation (12) into Equation (11) results in a formula, which is convenient for calculating the C-factor of a specific vegetation with a canopy cover c, fall velocity of the drops dripping from the vegetation on the soil V, average acute angle (degrees) of leaves and branches to the plant stem α and maximum volume of the interception store for particular crop or vegetation cover $IR_{\max}$.

Values of the constant F_{C} have been calculated for the main field crops and perennials using a regression analysis of two data sets – calculated proportions of impacting energies according to equation (12) and values of the C-factor obtained by long-term field plot measurements.

Illustration. Equation (9) is applied to estimate the impacting energy of 30 mm rainfall of intensity 30 mm h^{-1} on four types of agricultural plants: wheat, maize, alfalfa and apple orchard for the period May – August. The input parameters needed for resolving equation (9) were set in accordance with data from measurements presented in different literature sources. Figures 1, 2 and 3 illustrate some results from the application of equation (9).

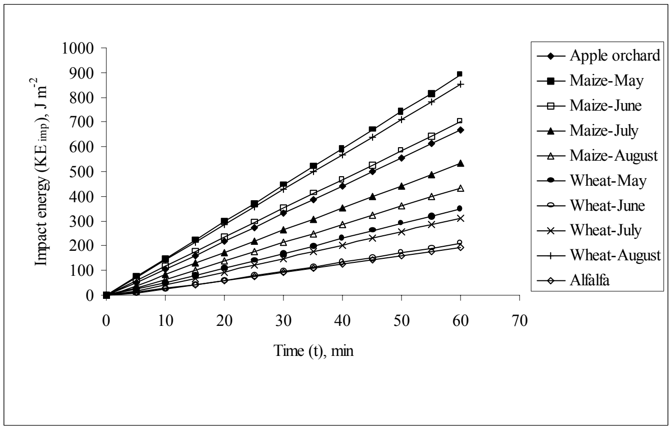

Figure 1. Impacting energy of simulated rainfall with intensity of 30 mm h^{-1} calculated according to equation (9) for different plants and months with high erosion risk.

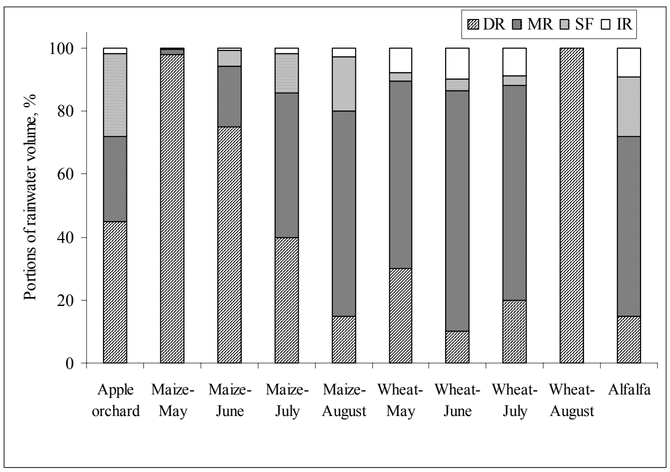

Figure 2. Estimated percentage portions of rainwater: directly reaching the ground (*DR*), reaching the ground as modified by the vegetation (*MR*), reaching the ground through flow down the leaves and stems (*SF*) and intercepted by the vegetation (*IR*), for months with high erosion risk. The amount of rainfall is 30 mm and the intensity – 30 mm h^{-1}.

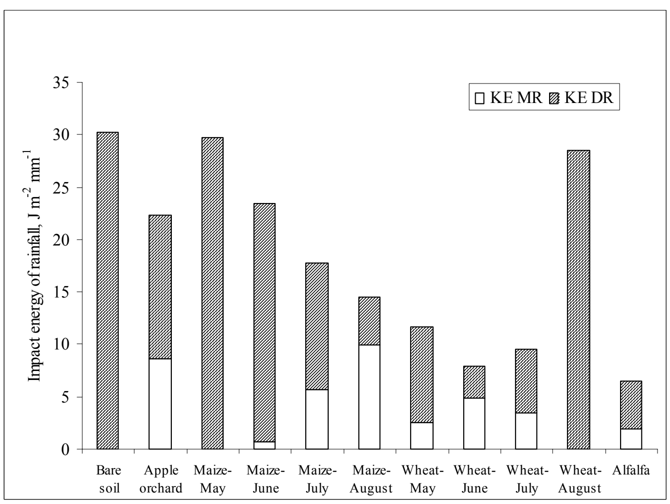

Figure 3. Estimated impact energy of 30 mm rainfall with intensity 30 mm h^{-1} for different plants and months with high erosion risk.

Reliability. The reliability of this approach for assessing the rainfall impacting energy on soil with vegetation canopy cover was estimated comparing the KE_{MR} values calculated with equation (9) for wheat, maize, alfalfa and apple orchard for the period April – August with the respective values calculated according to an already approved model for calculating the kinetic energy of the leaf drainage as:

(13) $KE_{MR} = 15.8\ (H_{eff})^{0.5} - 5.87$

The mean of the differences between the values of KE_{MR} calculated by these two approaches is 0.77 J m^{-2} mm^{-1} and it has not been found to be statistically significant as proved by t-test ($p = 0.014$). These findings are well visualised in Fig. 4 showing the KE_{MR} estimates according to equation (13) versus these calculated by equation (9). Fig. 4 shows well also one disadvantage of the estimates of equation (13): the values of KE_{MR} at effective height of vegetation lower than 0.13 m are negative. Obviously, the equation proposed in this study does not show such disadvantage, assigning close to zero but still positive values of KE_{MR}.

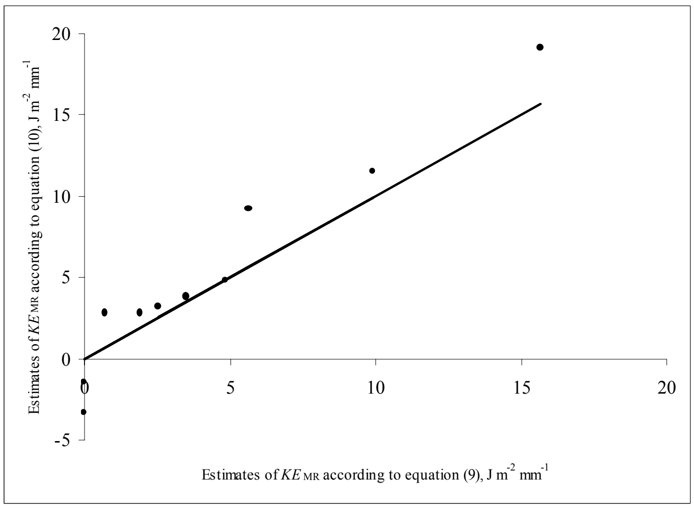

Figure 4. Estimated impact energy (KE_{MR}) of modified-by-vegetation rainfall according to equation (13) versus respective estimates by equation (9). Straight line represents 1:1 coincidence.

Application. The approach for estimating cover and management factor was applied for the purposes of a geographic information system for soil erosion risk assessments on the territory of Bulgaria at a scale of 1: 100 000. Values of mean monthly canopy cover (*c*), effective plant height (H_{eff}), average acute angle (degrees) of leaves and/or branches to the plant stem (α), maximum volume of the interception store (IR_{max}), fall velocity of the drops dripping from the vegetation on the soil (V) were set for main field crops and perennials in accordance with data from measurements presented in different literature sources. C-factor values were calculated for wheat, maize, sunflower, potatoes, tobacco, beats, alfalfa, vineyards and orchards using equations (11) and (12) with respect to rainfall erosivity monthly distributions for each of the 47 agro-ecological regions distinguished on the country's territory. The data in tables 1 and 2 show that the approach applied for assessing the cover and management factor has resulted in reasonable estimates of values for the main field crops and perennials grown on the territory of Bulgaria.

Table 1. Mean, minimal and maximal values and standard deviations of the crop and management factor (C) of the main field crops estimated for 47 agro-ecological regions distinguished on the territory of Bulgaria.

Parameter \ Crop	Wheat	Wheat*	Maize	Maize*	Sunflower	Tobacco	Potatoes	Beats	Alfalfa
Mean	0.22	0.28	0.39	0.50	0.32	0.71	0.69	0.34	0.07
St.Dev.	0.05	0.04	0.06	0.04	0.05	0.08	0.03	0.05	0.02
Minimum	0.12	0.16	0.27	0.42	0.20	0.51	0.62	0.22	0.04
Maximum	0.32	0.34	0.52	0.59	0.44	0.84	0.75	0.44	0.10

* For eroded lands

Table 2. Mean, minimal and maximal values and standard deviations of the crop and management factor (C) of vineyards and orchards estimated for 47 agro-ecological regions distinguished on the territory of Bulgaria.

Parameter \ Canopy	Orchards			Vineyards	
	8x8m c*=0.35	8x8m c=0.60	Palmette	c=0.35	c=0.24
Mean	0.42	0.30	0.39	0.64	0.70
St.Dev.	0.08	0.04	0.06	0.05	0.03
Minimum	0.24	0.21	0.26	0.54	0.62
Maximum	0.58	0.39	0.51	0.74	0.77

* Canopy cover

Soil erodibility factor (K)

Index of soil detachability based on laboratory measurements can substitute the USLE soil erodibility factor (K). The laboratory test is based on complete orthogonal second order design of two factors with three levels to find the optimal values of the test parameters ensuring minimal standard deviation of the output. The soil detachability index (*I*) is defined as the mass of aggregated soil (*m*) detached into micro aggregates and particles finer than 1 mm per unit water drop kinetic energy dispersed into breakdown of the aggregates (*KE*):

$$I = \frac{m}{KE} \; [\text{g J}^{-1}]$$

Statistical analyses have shown that soil detachability indices measured for 11 soils representing wide range of textures were well correlated with respective soil erodibility factor values measured from field plots.