Eurasian Soil Science, Vol. 35, No. 11, 2002, pp. 1237–1242. Translated from Pochvovedenie, No. 11, 2002, pp. 1397–1403.

SOIL EROSION

Parameters of Interrill Erodibility in the WEPP Model

S. Yu. Bulygin[1], M. A. Nearing[2], and A. B. Achasov[1]

[1]Sokolovskii Institute of Soil Science and Agrochemistry, ul. Chaikovskogo 4, Kharkov, Ukraine
[2]National Soil Erosion Research Laboratory, US Department of Agriculture, West Lafayette, IN, USA

Received February 22, 2001

Abstract—The results of investigations into interrill erodibility as determined by the WEPP method are considered. Limitations in the applicability of the WEPP model are discussed. The potential for its correct adaptation and modernization is evaluated.

INTRODUCTION

According to the materials of the summit in Rio de Janeiro (1992), soil erosion is the main cause of land degradation on a global scale. Processes of water erosion are responsible for 56% of land degradation, and those of wind erosion, for 28%. The same situation is typical of Russia and Ukraine. Solutions to numerous problems connected with soil erosion should be based on a profound knowledge of its nature. In this respect, mathematical models of soil erosion are very helpful, especially if they allow one to predict soil erosion on the basis of limited or incomplete data. To a great extent, the design and construction of erosion-resistant landscapes depend on the reliability of erosion prediction models.

The model used in the water erosion prediction project (WEPP) is one of the most promising models owing to its profound theoretical basis and successful mathematical formalization of the essence of physical processes of soil erosion. This model implies fundamental laws governing overland water flows [7].

According to the basic ideology of the WEPP, eroded land consists of zones subjected to (1) rill erosion and (2) interrill erosion [6]. Splash erosion and sheet erosion are believed to be dominant in the zone of interrill erosion, whereas soil detachment and removal by water flows predominate in the zone of rill erosion. The zone of interrill erosion in supposed to be the main source of sediment.

The following equation is used in our study to describe erosion:

$$dG/dx = D_i + D_r, \qquad (1)$$

where G is sediment load, kg/s m; x is a downslope distance, m; D_i is the delivery rate of sediments from the interrill zone to rills, kg/s per m^2; and D_r is the rate of soil loss or sediment deposition, kg/s per m^2.

Interrill erodibility (K_i), rill erodibility(K_r), and the threshold shear stress (τ_c) are the parameters that have to be determined prior to the use of the model. To attain a superiority of the theoretical WEPP model over empirical models (e.g., the USLE model), it is necessary to solve the problem of the erodibility determination. The present paper deals not only with this problem but also with the task of adaptation of the WEPP model.

OBJECTS AND METHODS

The determination of the erodibility parameters of chernozems was carried out in 1998–1999. Both the rill and interrill erodibility parameters were determined in the course of field experiments in accordance with the WEPP procedure.

Processes of rill erosion were simulated by means of flooding the experimental plot with the use of a standard procedure in triple replication [5]. The length of the experimental plot was 3 m, and its width, 0.15 m. Experiments were performed at the Donetsk Experimental Station of the Institute of Soil Science and Agricultural Chemistry. All of the six experiments were conducted on trial fields of a long-term crop rotation experiment initiated in 1989. The first experiment (site 1) was conducted on all the fields of an eight-year crop rotation system with moldboard tillage. This experiment was used as the control. The second experiment (site 2) was conducted on a field with non-inversive tillage to the same depth as in the first site. In the third experiment (site 3), shallow (6–8 cm) non-inversive tillage was applied. Finally, the fourth experiment (site 4) was conducted on a field with alternation of moldboard plowing (once every four years) with deep non-inversive tillage.

All the sites have similar soils: slightly eroded heavy loamy ordinary chernozems developed from loess. The organic carbon content is about 2%, and the content of physical clay (<0.01 mm) is 53%.

Two additional sites were studied. Site 5 represented a field with moderately eroded heavy loamy ordinary chernozem with the organic carbon content of 1% and the physical clay content of 50%. Site 6 was located on virgin land with medium-deep and medium-humus

(C_{org} 4%) heavy loamy (55% physical clay particles) ordinary chernozem.

The experiments were conducted in the beginning of May 1998, when the soils were in a normal physical state [10]. Prior to the experiments on the virgin land, the sod layer was removed from the soil surface.

The following procedures were used in our investigation. To calculate the flow velocity (v, m/s), the method of water pigmentation was used. The flow velocity was calculated as follows:

$$v = L/t_1, \qquad (2)$$

where L is the length of the experimental plot and t_1 is the duration of the flow of pigmented water across the plot (L), s. The v value was then multiplied by a factor of 0.6 in order to take into account the braking action of the flow bed. Water discharge (Q, m^3/s) was determined via filling up the reservoir of volume V (m^3) during the time t_2 (s):

$$Q = V/t_2. \qquad (3)$$

The cross-sectional area of the flow (A, m^3) was calculated as follows:

$$A = Q/v. \qquad (4)$$

The wetted perimeter of the flow (P, m) was calculated from

$$P = b + 2h, \qquad (5)$$

where b is the width of the flow bed, m; h is the depth of the flow, m; and $h = A/b$.

The specific discharge of the flow (q, m^2/s) was calculated from

$$q = Q/P. \qquad (6)$$

The hydraulic radius of the flow (R, m) was found from

$$R = A/P. \qquad (7)$$

The shear stress of the flow (τ, Pa) was calculated from

$$\tau = \rho g R S, \qquad (8)$$

where ρ is the density of water ($\rho = 1000$ kg/m^3); $g = 9.81$ m/s^2; and S is the slope steepness.

The shear stress can also be calculated from the following equation:

$$\tau = \rho g (v^2/C^2), \qquad (9)$$

where C is the Chezy coefficient.

Specific sediment discharge (Q_s, kg/m s) is equal to

$$Q_s = qM, \qquad (10)$$

where M is the turbidity of water, kg/m^3.

The Chezy coefficient C can be calculated as

$$C = 8/f^{1/2}, \qquad (11)$$

where f is the Darcy–Weisbach coefficient. It can be calculated by the Shaw formula

$$f = 8gRS/v^2. \qquad (12)$$

The rill erodibility factor K_r and shear stress (τ_c) can be determined by the graphic–analytical method. For this purpose, data on Q_s should be plotted against τ in Cartesian coordinates and approximated by a straight line. An inclination of this line is equal to the factor of rill erodibility. Its intersection with the abscissa is equal to the threshold shear stress.

Processes of interrill erosion were also studied on trial fields of the Donetsk experimental station. The additional sites were located in the experimental farm "Udarnik" of the Lugansk Institute of Agroindustrial Production (site 7) and the experimental farm "Lesnaja Stenka" of the Kharkov Institute of Soil Science and Agricultural Chemistry in Kharkov oblast (sites 8–13). Soil properties at these sites are given below.

Site 7, low-humus medium-deep chernozem originated from loess; the soil contains 2% organic carbon and 50% silt and clay (<0.01 mm). In the year of study, it was under buckwheat.

Site 8, low-humus shallow chernozem originated from mottled clay underlain by sands; C_{org}, 1.2%; silt and clay content, 43%; the experiment was performed after harvesting winter wheat.

Site 9, low-humus chernozem originated from mottled clay underlain by sands; C_{org}, 0.9%; silt and clay content, 35%; the experiment was performed after harvesting winter wheat.

Site 10, low-humus, deep, deeply effervescent chernozem originated from reddish brown clay underlain by sands; C_{org}, 1.3%; silt and clay content, 37%; buckwheat field.

Site 11, low-humus, deep, deeply effervescent chernozem originated from mottled clay underlain by sands; C_{org}, 1.5%; silt and clay content, 41%; the experiment was performed after harvesting winter wheat.

Site 12, low-humus, medium-deep, shallow-effervescing ordinary chernozem originated from loess; C_{org}, 2.7%; silt and clay content, 54%; the experiment was performed after harvesting winter wheat.

Site 13, low-humus, thin, shallow-effervescing ordinary chernozem originated from loess; C_{org}, 2.6%; silt and clay content, 44%; buckwheat field.

All experiments were conducted on cultivated fields in May and June 1999 with the use of a portable rain simulator. The simulator designed by Carlos B. Irurtia [4] is very convenient to use. The intensity of artificial rain varies from 0.5 to 5.0 mm/min.

The simulated rain covers a square parcel of land 0.5 × 0.5 m in size. All plants and plant residues were removed from the parcel prior to rain simulation. Four rain intensities in two replicates were used on every experimental plot. The duration of each simulation under a constant rain intensity was 10 min. The first simulation in each sequence was the one with the lowest rain intensity. In order to attain a standard state of soil (that is, to saturate it with water), records were taken only after achieving a constant rate of runoff from the plots. In the course of rainfall simulation (at a constant intensity), water samples were taken in order to determine the water turbidity (M). The total runoff (V) and slope inclination were also measured.

The following equation was used to calculate the interrill erosion:

$$D_i = MV/T/S, \qquad (13)$$

where S is the area of the plot, m^2.

In 1969, Meyer and Wishmeier suggested that the interrill erosion could be described by the following equation:

$$D_i = K_i I^p, \qquad (14)$$

where D_i is the measure of interrill erosion, kg/m^2 per s; K_i is the coefficient of interrill erodibility of soil, kg s/m^4; I is the intensity of rain, m/s; and p is the regression coefficient.

The effect of slope inclination on the interrill erodibility is assessed from the equation describing changes in the transportation capacity of interrill water flows:

$$D_i = K_i I^p S_f, \qquad (15)$$

where S_f is the slope factor that can be calculated with the use of the equation proposed by Liebenow *et al.* [9]:

$$S_f = 1.05{-}0.85\exp(-4\sin\alpha), \qquad (16)$$

where α is the slope inclination in degrees.

The resulting equation, which was used in the WEPP model [6], is as follows:

$$D_i = K_i I^2(1.05{-}0.85\exp(-4\sin\alpha)). \qquad (17)$$

The coefficient of interrill erodibility of soil K_i was determined with the use of a graphic–analytical method. Data on D_i were plotted against I^2S_f in Cartesian coordinates and approximated by a straight line. The inclination of this line is equal to the factor of interrill erodibility of soil, K_i. The intensity of soil loss is supposed to be proportional to this factor.

A number of attempts were undertaken to improve the model of interrill erosion. For example, Zhang *et al.* [12] proposed the equation

$$D_i = K_i I q^{1/2} S^{2/3}, \qquad (18)$$

where q is the water flow discharge, m^2/s, and S is the inclination of slope, %.

Table 1. Scouring velocities of bottom flows

Site no.	d, m 10^{-3}	v_Δ, m/s	Soil bulk density, g/cm^3	v_Δ^*, m/s
1	0.72	0.11	1.0	0.11
2	0.94	0.12	1.1	0.12
3	0.98	0.13	1.1	0.13
4	0.92	0.12	1.0	0.12
5	0.94	0.12	1.1	0.12
6	1.98	0.24	1.4	0.30

* Scouring bottom velocity v_Δ corrected for the tenacity of soil related to its bulk density.

Table 2. Threshold shear stress (τ_c) as influenced by the method of its determination

Site no.	v_Δ, m/s	R', m	Inclination, $\tan\alpha$	τ_c, Pa	τ_c'', Pa	K_r
1	2	3	4	5	6	7
1	0.11	0.0049	0.035	0.13	1.68	0.058
2	0.12	0.006	0.034	0.08	2.00	0.057
3	0.13	0.017	0.014	0.26	2.33	0.058
4	0.12	0.023	0.009	0.08	2.03	0.119
5	0.12	0.004	0.056	2.45	2.19	0.032
6	0.30	0.010	0.123	0.04	12.1	0.001

Another effort was made by Bradford and Foster [3], who worked out the equation

$$D_i = K_i I q S_f. \qquad (19)$$

RESULTS AND DISCUSSION

Concurrently with field experiments, the bulk density of the top 10-cm-thick soil layer was determined together with the mean weighted diameter of water-stable aggregates (d). With the use of these data, the bottom scouring velocity was calculated v_Δ [2]. The results of the first series of experiments that was aimed at the determination of rill erodibility parameters are presented in Table 1.

The values of bottom scouring velocity without correction for the soil bulk density characterize soil erodibility in the normal conventional state [10].

The outcome of rill erosion simulation includes data on the shear stress (τ_c) and the rill erodibility parameter (K_r). Both of these were determined with the use of the extrapolation method (Table 2).

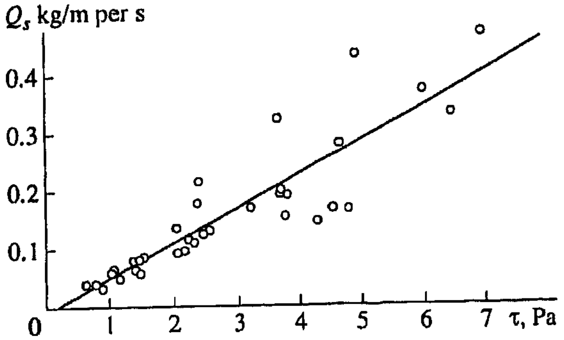
The resulting value of threshold shear stress in the case of virgin land (site 7) appeared to be extremely small (τ_c = 0.04 Pa). The highest shear stress in this experiment (13 Pa) appeared to be insufficient to over-

Table 3. Results of physical simulation of rain erosion

Site no.	Islope, °	Rain intensity I, mm/min	Turbidity, g/l	Runoff volume V, l	Interrill erosion D_i, g/m^2 per s	Coefficient of interrill erodibility (Eq. 17) K_i), t s/m^4
4	0.8	0.50	1.92	0.12	0.002	1581.3
	0.8	1.10	2.88	0.74	0.014	3027.3
	0.8	1.70	4.70	1.60	0.050	4472.3
	0.8	2.30	4.96	2.30	0.076	3706.6
7	3.5	1.70	4.45	0.84	0.025	507.5
	3.5	2.30	11.88	4.00	0.317	3524.9
	3.5	2.70	27.82	4.80	0.890	7187.8
	3.5	2.90	34.98	9.43	2.199	15388.5

come the threshold shear stress characteristic of the soil. This is because the corresponding value of soil loss was as low as 0.035 kg/m per s. Even a smaller shear stress ($\tau = 6.9$ Pa) (figure) on the arable land (site 1) led to a much higher soil loss ($q_s = 0.48$ kg/ms). As a rule, the relationship between q_s and τ follows the second-order parabolic curve if τ is less than the threshold value [11]. First-order curves (straight lines) can only be applied in the case when the shear stress of the flow exceeds the threshold value [7]. The transitional point from the line to the curve corresponds to the threshold shear stress. In our case, the use of linear extrapolation led to erroneous estimates.

We have also used an alternative method of threshold shear stress determination based on the use of the threshold bottom velocity of the flow (Table 2, column 2). The latter depends on soil properties that directly determine its erodibility. The threshold velocity corresponds to the transitional point on the curve relating the intensity of soil loss to the flow velocity [2, 11].



Specific sediment discharge (Q_s) as influenced by shear stress (τ) for an ordinary chernozem (site 1, the Donetsk experimental station).

The following method of the threshold shear stress (τ_c) determination on the basis of data on the threshold bottom velocity (v_Δ) seems reasonable. The bottom velocity of the flow is calculated by the Goncharov formula:

$$v_\Delta = 1.25v/\log(6.15H/\Delta). \qquad (20)$$

The roughness of the surface (Δ) is calculated as $\Delta = 0.7d$, where d is the mean weighted diameter of water-stable aggregates. In our case, the ratio v/v_Δ appeared to be in the range of 1.0–1.5, which made it possible to calculate the hydraulic radius directly from data on the scouring velocity of bottom flow v_Δ. Earlier, it was noted that the threshold shear stress depends on certain soil properties. Hence, it can be predicted with the use of these. In particular, the threshold shear stress closely correlates with the threshold bottom velocity that, in turn, depends on the physical properties of the soil. To make use of them, it is necessary to determine coefficient (f) in the Darcy–Weissbach formula. If rill erosion occurs on a bare soil, then this coefficient can be equated to 1.11 [7] and the desired value of the hydraulic radius can be found from (12) as follows:

$$R' = (v^2 f)/(8gS). \qquad (21)$$

The values of hydraulic radius calculated according to Eq. (21) are presented in column 3 (Table 2). The mean flow velocity (v) is assumed to be equal to the bottom scouring velocity (v_Δ). The predicted values of the threshold shear stress (τ'_c) are presented in column 6 (Table 2).

Field experiments with the use of the rain simulator gave evidence that the coefficient of interrill erodibility (K_i) is a function of rain intensity. This conclusion makes clear the reason behind the scarcity of rain intensities used by those investigators who contributed greatly into the WEPP development. In particular,

Table 4. Coefficient of interrill erodibility (K_i) as influenced by the method of its determination

Site no.	K_i (t s/m^4) calculated from Eq. (19): $D_i = K_i \times I^2 \times S_f$	r	K_i (t s$^{1/2}$/m^4) calculated from Eq. (18): $D_i = K_i \times I \times q^{1/2} \times S^{2/3}$	r	K_i (t s$^{1/2}$/m^4) calculated from Eq. (19): $D_i = K_i \times I \times q \times S_f$	r	K_i (t s$^{1/2}$/m^4) calculated from the equation proposed by us: $D_i = K_i \times I \times q \times S^{2/3}$	r
1	2	3	4	5	6	7	8	9
1	52.2	0.95	2.7	0.95	382.7	0.95	1113.6	0.95
2	77.4	0.98	2.9	0.97	290.7	0.93	869.7	0.93
3	156.1	0.88	10.1	0.94	675.9	0.94	3064.9	0.94
4	152.3	0.84	12.3	0.97	1056.8	0.99	4486.4	0.99
5	510.7	0.92	17.3	0.87	2561.0	0.90	6140.3	0.90
7	3318.0	0.89	63.5	0.95	4095.7	0.99	10135.9	0.99
8	466.2	0.69	17.7	0.84	2526.4	0.93	5722.7	0.93
9	80.5	0.71	4.4	0.87	986.6	0.96	2312.4	0.96
10	51.1	0.63	3.1	0.96	504.2	0.99	1161.4	0.99
11	117.7	0.93	3.9	0.95	530.1	0.96	1231.9	0.96
12	340.6	0.85	13.2	0.93	1453.9	0.99	3953.8	0.97
13	262.5	0.79	10.9	0.92	1086.4	0.96	3123.8	0.97

Note: Correlation coefficients characterize the degree of connectedness between the D_i and the parameters of rain and topography.

Bradford and Foster [3] used only one rain intensity ($I = 72$ mm/h), whereas Laflen *et al.* applied two different rain intensities (63 and 125 mm/h) [8]. In any case, the coefficient of interrill erodibility cannot be determined by the graphic–analytical method on the basis of these data. In our experiment on similar soils (sites 4 and 7), the coefficient of interrill erodibility depended on the rain intensity (Table 3). Such behavior is in accord with the nonlinear relation between D_i and I_2S^f over the range of relatively high rain intensities.

This is why it seems reasonable to standardize the experimental method for the determination of the coefficient of interrill erodibility. Taking into account the architecture of the WEPP model and the commonly accepted principles of soil erosion modeling, it is advisable to base the simulation on the intensity of rain, which is typical of the territory in question. For this purpose, we divided the territory of the Ukraine into districts differing by typical rain intensities (according to stochastic ratings of rainfalls) [1].

For each of the thirteen districts, a formula of a typical pluviograph was prepared with due account for the probability of rains of the given intensity. In our case of water erosion modeling, a 10% probability seemed to be sufficient (i.e., rains of the given intensity may occur once in ten years). Data on rain intensities for site 4 (Table 3) assume the rains of 10% probability in the eastern part of Ukraine.

Data presented in Table 4 (except for site 7) were calculated with the use of the pluviograph typical of the region and the four intensities of simulated rain. Data on K_i were calculated with the use of different models (Table 4). The quality of prediction models can be judged from coefficients of correlation between the D_i and the parameters of surface runoff. The resulting values of K_i appear to be extremely different. Hence, erosion predictions by the WEPP model should also be extremely different depending on the chosen model for the K_i. Moreover, not only the absolute values but also the dimensionality of K_i may be different, as seen from the equation suggested by Zhang *et al.* (1998). From our point of view, this is incorrect. The closest correlation between the D_i and the factors of surface runoff (I_2S^f) was achieved with the use of the model compiled by us (Table 4, columns 8 and 9).

These data prove the necessity of standardizing the method of K_i determination. Meanwhile, in order to provide comparable results, it is advisable to use Eq. (17).

The alternative method of K_i determination depends on regression equations relating this coefficient to soil properties. It is evident that data bases on soil parameters in the WEPP model developed for soils of the United States are not applicable to soils of the Ukraine. Therefore, we have conducted rain simulation experiments in order to determine K_i for soils of the Ukraine. Experimental values of K_i appeared to correlate closely with the organic matter content and texture of soil. The following regression equation was obtained:

$$Y = 455.9 - 95.5X_1 - 107.1X_2 + 24X_3, \qquad (22)$$

where Y is the coefficient of interrill erodibility; X_1 is the humus content, %; X_2 is the content of coarse sand

(1–0.25 mm) fraction, %; and X_3 is the content of fine silt fraction (0.005–0.001 mm), %.

The correlation coefficient r is equal to 0.82 with a confidence level of 95%. Equation (22) makes it possible to avoid field experimentation and calculate K_i with the use of commonly available data on soil properties. The applicability of this model is evidently restricted. The regression model (Eq. 22) is only applicable to soils similar to those of the studied test sites. Further experiments are necessary to widen the applicability of the model.

CONCLUSION

The possibility of adequate calculation of the parameters of interrill erodibility on the basis of available data on soil properties has been proven. The application of the WEPP model for Ukrainian soils requires standardization of the method of determination of the coefficient of interrill erodibility. At the same time, the original formula from the WEPP documentation can be successfully applied to compare the results obtained at different plots by different researchers.

ACKNOWLEDGMENTS

This work was supported by the ARS USDA, grant no. 58-3602-8F015.

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ПРЕДИСЛОВИЕ

к статье С.Ю.Булыгина, М.А.Неаринга, А.Б.Ачасова "Параметры межручейковой эрозийной стойкости почв в модели эрозии WEPP"

Эрозия почвы обусловлена многими природными и антропогенными факторами, проявление ее характеризуется большой неоднородностью даже в пределах одного поля. Поэтому нерационально определять размеры эрозии в целом по стране, региону или на отдельных полях путем ее прямого учета на многочисленных участках. В настоящее время для оценки интенсивности эрозии почв все шире используются расчетные методы — модели прогноза. Возможность прогнозирования эрозионных процессов при различных типах землепользования и агротехники позволяет выбрать наиболее приемлемые альтернативы для их предупреждения.

За последние 20-30 лет учеными предложено большое количество моделей водной эрозии почв. Наиболее распространенной в аспекте практического приложения является эмпирико-статистическое универсальное уравнение потерь почвы Уишмейера и Смита — Universal Soil Loss Equation (USLE) и его переработанный вариант (RUSLE). Эти уравнения до настоящего времени рассматриваются как мировой стандарт и применяются с различными модификациями во многих странах (1965, 1976, 1978).

В США разрабатываются новые поколения моделей для прогноза и предупреждения эрозии почв. Наиболее перспективной из них является “Проект прогноза водной эрозии” (Water Erosion Prediction Project—WEPP 1987, 1991, 1997). Модель WEPP моделирует предшествующие эрозии процессы с временным шагом в один день и основывается на концепции межручейковой и ручейковой эрозии.

Эффективность использования модели в значительной степени зависит от точности определения ее основных параметров. Отсутствие строгой методики экспериментального определения коэффициента межручейковой эрозионной стойкости почвы (K_i), используемого в модели WEPP, не позволяет адаптировать модель к конкретным почвенно-экологическим условиям. В связи с этим цель представленной статьи заключается в адаптации методики определения межручейковой эрозионной стойкости почвы для условий Украины.

Предложенный подход определения межручейковой эродируемости почвы может использоваться и для условий Беларуси. Поэтому представленная статья имеет научную значимость и практический интерес для специалистов в области эрозиоведения и почвозащитного земледелия республики.

Зав.лабораторией защиты почв от эрозии НИГП "Институт почвоведения и агрохимии", кандидат сельскохозяйственных наук Н.Н.Цыбулька

УДК 631.459:631.6.02

ПАРАМЕТРЫ МЕЖРУЧЕЙКОВОЙ ЭРОЗИОННОЙ СТОЙКОСТИ ПОЧВ В МОДЕЛИ ЭРОЗИИ WEPP*

С.Ю.Булыгин[1]
М.А.Неаринг[2]
А.Б.Ачасов[1]
[1] *Институт почвоведения и агрохимии им.А.Н.Соколовского (г.Харьков, Украина)*
[2] *Национальная лаборатория эрозии (Западный Лафайет, штат Индиана, США)*

Рассматриваются результаты исследований межручейковой эрозии почв, проведенных по методике модели WEPP. Показаны условия, при которых данная методика не позволяет корректно оценить эрозионную ситуацию. Представлены возможные пути усовершенствования методики.

Известно, что наиболее эффективным методом прогноза и оценки эрозионных потерь почвы является метод математического моделирования, результатом и продуктом которого становится модель процессов эрозии. В настоящее время одной из наиболее перспективных моделей водной эрозии считается Water Erosion Prediction Project (WEPP). Это обусловлено теоретическим характером модели и удачной физико-математической формулизацией процессов эрозии.

В то же время необходимо отметить, что некоторые, прежде всего методические, недостатки модели WEPP могут привести к значительным погрешностям при оценке эрозионной ситуации [1]. Цель данной работы — адаптация методики WEPP относительно определения параметров межручейковой эродируемости почвы

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* *Работа выполнена при финансовой поддержке ARS USDA № 58-3602-8F015.*

для условий Украины.

Согласно идеологии модели WEPP, любую территорию можно разделить на зоны ручейковой и межручейковой эрозии [4, 7]. Считается, что в межручейковой зоне доминируют процессы капельной эрозии и плоскостного мелкого смыва, а в ручейковой зоне — процессы размыва почвы потоком и транспортировании седиментов. При этом зоны межручейковой эрозии являются главными поставщиками седиментов в ручейки. Такой подход не является бесспорным, но он предоставляет существенные преимущества для математических расчетов процессов эрозии.

В 1969 г. p.Meyer и Wishmeir предложили общее уравнение, которое описывает процесс межручейковой эрозии:

$$D_i = K_i \cdot I^p, \qquad (1)$$

где D_i — величина межручейковой эрозии, кг/м²/с; K_i — эмпирический коэффициент межручейковой эрозионной стойкости почвы, кг · с/м⁴; I — интенсивность дождя, м/с; p — коэффициент регрессии.

Влияние уклона поверхности почвы на межручейковую эрозию учитывается через изменение транспортирующей способности межручейкового потока:

$$D_i = K_i \cdot I^p \cdot S_f \qquad (2)$$

где показатель S_f характеризует влияние уклона поверхности и рассчитывается по формуле, которую предложил Liebenow с соавторами [6]:

$$S_f = 1{,}05\text{-}0{,}85\exp(-4\sin\alpha), \qquad (3)$$

где α — уклон поверхности в градусах.

Поэтому полная формула определения параметров межручейковой эрозии, которая сейчас используется в модели WEPP [4], имеет следующий вид:

$$D_i = K_i \cdot I^p \cdot (1{,}05\text{-}0{,}85\exp(-4\sin\alpha)). \qquad (4)$$

В последнее время проводятся многочисленные попытки усовершенствования модели межручейковой эрозии. Так, например, Zhang с соавторами [8] предложил уравнения:

$$D_i = K_i \cdot I \cdot q^{1/2} \cdot S^{2/3}, \qquad (5)$$

где q — затраты воды с ширины стоковой площадки, м²/с; S — уклон поверхности в %.

Bradford и Foster [2] получили следующую формулу:

$$D_i = K_i \cdot I \cdot q \cdot S_f \qquad (6)$$

Необходимо отметить отсутствие строгой методики экспериментального определения K_i. Изменение формы уравнений, по нашему мнению, отражает не общие физические процессы, а скорее процессы, обусловленные разностью в объектах и методиках исследований. В то же время невозможно использовать для определения K_i почв Украины и других регионов регрессионные зависимости, полученные на почвах коллекции WEPP.

1. Характеристики исследуемых почв

№ точки	Почва	Содержание гумуса, %	ГС1	ГС2	ГС3	ГС4	ГС5	ГС6	Содержание физической глины, %
1	Чернозем обыкновенный слабоэродированный на лёссе (Донецкая исследовательская станция)	4,3	1,3	21,6	18,8	10,2	8,9	39,2	58,3
2		4,5	1,7	16,3	21,9	10,0	10,3	39,7	60,0
3		4,3	1,6	14,3	24,9	8,1	11,1	40,1	59,3
4		4,3	1,2	18,5	19,3	9,7	14,1	37,2	60,9
5	Чернозем обыкновенный среднеэродированный на лёссе (Донецкая исследовательская станция)	1,7	1,3	21,6	18,8	10,2	8,9	39,2	58,3
2а	Чернозем маломощный на песках (КСП "Лесная Стенка")	2,1	1,1	38,3	17,8	3,9	14,3	24,6	42,8
7а	Чернозем маломощный на песках (КСП "Лесная Стенка")	1,6	2,2	48,1	14,4	7,5	7,2	20,8	35,4
8а	Чернозем мощный глубоковскипающий на красно-бурых глинах (КСП "Лесная Стенка")	2,2	2,7	48,5	11,9	6,9	5,0	25,1	37,1
9а	Чернозем глубоковскипающий на пестроцветных глинах (КСП "Лесная Стенка")	2,5	3,8	35,8	19,1	5,6	8,3	27,5	41,4
12а	Чернозем обыкновенный среднемощный высоковскипающий на лёссовых породах (КСП "Лесная Стенка")	4,8	0,5	35,1	10,3	9,5	11,6	33,0	54,2
14а	Чернозем обыкновенный маломощный высоковскипающий на лёссовых породах (КСП "Лесная Стенка")	4,4	0,6	15,6	29,4	4,8	12,2	34,4	51,4
20	Чернозем обыкновенный на лёссовых породах (о.х. "Ударник")	3,6	0,6	21,6	17,0	12,2	8,7	30,7	51,6

Примечание. ГС1, ГС2, ГС3, ГС4, ГС5, ГС6 — фракции гранулометрического состава: ГС1 — 0,25-0,1 мм, ГС2 — 0,1-0,05 мм, ГС3 — 0,05-0,01 мм, ГС4 — 0,01-0,005 мм, ГС5 — 0,005-0,001 мм, ГС6 — <0,001мм.

2. Значения K_i, рассчитанные по различным формулам

№ точки	K_i т · с/м^4 (по формуле 4)	r	K_p т · с$^{1/2}$/м^4 (по формуле 5)	r	K_p т · с/м^4 (по формуле 6)	r	K_p т · с/м^4 (по предложенной нами формуле: $D_i = K_{ц} Iq \cdot S^{2/3}$)	r
1	52,2	0,95	2,7	0,95	382,7	0,95	1113,6	0,95
2	77,4	0,98	2,9	0,97	290,7	0,93	869,7	0,93
3	156,1	0,88	10,1	0,94	675,9	0,94	3064,9	0,94
4	152,3	0,84	12,3	0,97	1056,8	0,99	4486,4	0,99
5	510,7	0,92	17,3	0,87	256,1	0,90	6140,3	0,90
2а	466,2	0,69	17,7	0,84	2526,4	0,93	5722,7	0,93
7а	80,5	0,71	4,4	0,87	986,6	0,96	2312,4	0,96
8а	51,1	0,63	3,1	0,96	504,2	0,99	1161,4	0,99
9а	117,7	0,93	3,9	0,95	530,1	0,96	1231,9	0,96
12а	340,6	0,85	13,2	0,93	1453,9	0,99	3953,8	0,97
14а	262,5	0,79	10,9	0,92	1086,4	0,96	3123,8	0,97
20	3318,0	0,89	63,5	0,95	4095,7	0,99	10135,9	0,99

Примечание. Коэффициенты корреляции (r) характеризуют тесноту связи между Di и параметрами дождя и рельефа.

невозможно использовать зависимости, полученные на почвах США из коллекции WEPP, необходимо провести эмпирическое определение K_i для как можно большего количества различных по генезису почв Украины.

По результатам статистической обработки данных экспериментов в Донецке и КСП "Лесная Стенка" установлена важная зависимость между K_i и некоторыми генетическими характеристиками почвы — содержанием органического вещества и его гранулометрическим составом. По результатам обработки получено регрессионное уравнение:

$$Y = 455{,}9 - 95{,}5 \cdot X_1 - 107{,}1 \cdot X_2 + 24 \cdot X_3, \quad (8)$$

где Y — коэффициент межручейковой эрозионной стойкости почвы; X_1 — содержание гумуса, %; X_2 — содержание фракции гранулометрического состава 1,00-0,25 мм, %; X_3 — содержание фракции гранулометрического состава 0,005-0,001 мм, %.

Коэффициент корреляции r = 0,82.

Таким образом, появляется возможность определения K_i по данным гранулометрического состава и содержания органического углерода без проведения активного эксперимента. Отметим, что приведенная регрессионная модель, как и любая другая, имеет определенные ограничения: ее применение будет наиболее корректно для почв, близких к изучаемым. По всей вероятности, для почв иного генезиса статистическая формула определения K_i будет другой. Для изучения этого вопроса необходимо продолжение экспериментов на различных почвах.

Выводы

1. Успешное использование модели WEPP требует окончательного определения методики проведения дождевания для определения параметра K_i.

Для этого в первую очередь необходимо определиться с формулой расчета параметра K_i. Для сопоставления полученных различными исследователями результатов мы предлагаем применять формулу, официально используемую сейчас в модели WEPP.

2. Определения K_i необходимо проводить по результатам дождевания с несколькими различными по интенсивности режимами. При этом желательно установление стандартного набора интенсивностей дождя.

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