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ASSESSMENT OF THE SOIL INFILTRATION CAPACITY USING A PORTABLE RAIN SIMULATOR

Yu. P. Sukhanovskiy, V. A. Vytovtov, A. V. Prushchik, Yu. A. Solovieva, S. I. Sanzharova

All-Russian Research Institute of Arable Farming and Soil Erosion Control, 305021, Kursk, K. Marx st., Russia
e-mail: soil-er@kursknet.ru

Under consideration is the possible assessment of the soil infiltration capacity by using a portable rain simulator to irrigate a small area without the rill erosion development. To assess the soil infiltration capacity, an equation has been earlier suggested including the erosion index of rain AI to be a criterion of similarity. The equation was verified for natural rainfall (in catchments and runoff plots) as well as for artificial rainfall (in runoff plots 5 m long and 5 m^2 in area). It was shown that the small-sized runoff plots display no rill erosion and can be used for assessing the soil infiltration capacity. To verify this affirmation, two experiments were conducted, one of them included a large rain simulator and a runoff plot in field (3 m long and 3 m^2 in area, where the rill erosion occurred); in the other experiment carried out in laboratory with the use of soil monoliths taken in the same field a portable rain simulator and a runoff plot shaped as a cycle with the area of 0.05 m^2 were used (without the rill erosion development). Every rain simulator revealed the same size of raindrops, they fell from the same height; the rainfall intensity was constant, but the values of these parameters seemed to be different. The dependence between the soil infiltration capacity and the index of rain AI proved to be very close in both experiments. The use of the portable rain simulator requires expenditures to a lesser extent.

Keywords: natural and artificial rainfalls, criterion of similarity, infiltration, runoff plots, chernozem.

INTRODUCTION

Sprinkling of runoff plots found an application with the view of studying the soil erosion in the 1940s, being associated with the study carried out by Zingg (1940). This research is predominantly oriented to study the soil loss and the surface runoff of rain water that is mainly dependent on the soil infiltration capacity. In this case the size of runoff plots has to provide the rill erosion development, i.e. the soil is washed out by water flows. The question how to use the obtained experimental data for studying the effects of natural rainfall has been a subject of studies for several decades.

The concept of similarity widely adopted for physical modeling proved to be suitable for these studies. The natural and artificial rainfall should be considered as similar ones if they exert the same effect on the soil surface. A physically-based erosion index of rain AI was suggested by the author in 2002 to be a criterion of similarity for the erosion-induced soil loss [5–7]. It means that the soil loss caused by natural and artificial rainfall is the same when the values of this index are similar. Having used the criterion of similarity, the data obtained by sprinkling of runoff plots can be used for calculating the loss of soils washed out by natural rainfall. In 2003 it has been also established that this index is a criterion of similarity for the soil infiltration capacity [4]. This affirmation was verified by measurement data of the rain runoff obtained at the territory of water-balanced Nizhnedevitskaya experimental station in the Voronezh region (the experiment was conducted on chernozems by using runoff plots 40–132 m long and catchment – 0.05–3.16 km^2). To study the soil infiltration capacity, there are no limits for the size of runoff plots. It must be only said that with increasing the size of runoff plots the experiment expenditures become increased as well.

The given paper is aimed at studying the possible assessment of the soil infiltration capacity using a portable rain simulator with small irrigation area and without the rill erosion development.

OBJECTS AND METHODS

Sprinkling of runoff plots was applied to study the soil infiltration capacity during the rainfall. Two kinds of rain simulators (RS) were used as constructed on the same principle: the same size of raindrops to be fell from the same height, the constant rain intensity. As seen from Fig. 1, the large rain simulator was used for studying the erosion-hydrological processes in runoff plots 3 m long and 1 m wide (the irrigation area is 3 m^2) [1]. This experiment was conducted on chernozem used as a fallow in the grain-fallow rotation' it revealed the

Fig. 1. The large rainfall simulator in the runoff plot 3 m^2 long.

formation of rill erosion. The second experiment was conducted in laboratory by using two soil monoliths taken in the same field. A portable rain simulator applied in a runoff plot shaped as a cycle with the area of 0.05 m^2 displayed no rill erosion (Fig. 2) [2]. Parameters of both rain simulators are presented in Table. The sprinkling was based upon the methods described earlier [5].

The rain intensity (I_{rain} mm/min) was constant; the surface of the runoff plot covered by a moisture-resistant film permitted to determine it. The water volume flown down the runoff plot (ΔV_i l) was taken during definite time intervals (Δt_i min), where i is a number of the water volume corresponding to time interval t. The runoff intensity ($I_{run,i}$, mm/min), i.e. the water volume flown from the area unit for the time unit was calculated using the following dependence:

$$I_{run,i} = \Delta V_i/(\Delta t_i S). \quad (1)$$

This dependence was used to calculate the rain intensity (I_{rain}) averaged for the time interval (Δt_i) in the following way:

$$I_{inf} = I_{rain} - 1_{run.i}\,. \quad (2)$$

Fig. 2. The portable rainfall simulator in the area of runoff plot of 0.05m^2.

Parameters of rain simulators and experimental data

Parameter	Large RS	Portable RS	
		1*	2*
Area of the runoff plot, m^2	3.0	0.05	0.05
Diameter of raindrops, mm	4.5±0.3	4.0±0.3	4.0±0.3
Height of raindrop fall, m	2.0	1.0	1.0
Velocity of raindrop fall, m/s	5.53	4.12	4.12
Rain intensity, mm/min			
Initial	1.54±0.07	2.35±0.07	2.39±0.04
final	1.67±0.03	2.28±0.06	2.36±0.11
Time of the runoff beginning, min	3.5	2.0	1.5
$AI_{кр}$, *t*-m/ha	8.8	8.7	6.7
$K_{уст}$, mm/мин	0.21±0.02	0.25±0.06	0.19±0.08

* No. of soil monolith (replication)

Under the given conditions of sprinkling this intensity helps to assess the soil infiltration capacity (K_i). Under the other similar conditions for different rainfall (artificial and natural) the soil infiltration capacity is recommended to be approximated by the following equation:

$$K(t) = K_{\min} + (K_{\text{kp}} - K_{\min})\exp[-\alpha(\frac{AI(t)}{AI_{\text{kp}}} - 1)], \quad (3)$$

where $K(t)$ is the soil infiltration capacity in any time moment from the rainfall beginning, mm/min; $K_{\min}$ – the minimal infiltration capacity, mm/min; $AI(t)$ – erosion rain index to the time moment t, t-m/ha; $AI_{\text{kp}} = AI(t_{\text{kp}})$, where t_{kp} – time for the runoff; K_{kp} – infiltration capacity at the beginning of the runoff (it is equal to the rain intensity corresponding to AI_{kp}) mm/min; a – an unknown parameter that is dependent on properties and state of soil; t-m is the mixed product of ton and meter widely adopted for the empiric erosion rain index EI (Wischmeier, 1978). During the different rainfall the runoff starts when this index reaches the AI_{kp} value. The $K_{\min}$, K_{kp} and AI_{kp} values are assessed by measurement data obtained in the course of experiment and a value – under conditions in which the measured K_i value well agrees with that calculated by the equation (3), the latter being used for any natural rainfall preliminary calculated $AI(t)$ for it. Having determined AI_{kp} and $AI(t)$ it is possible to detect the time of the runoff beginning t_{kp} and K_{kp} value as the intensity of natural rainfall corresponding to this time [4]. The runoff layer is determined by exceeding the rain intensity over the soil infiltration capacity, i.e. $[I_{\text{rain}}(t) - K(t)] > 0$.

For the rain with the constant intensity, the same size of raindrops fell with the similar velocity from the same height the erosion characteristics have been obtained through the following equation:

$$A(t) = \frac{1}{2}\rho V I_{\text{rain}}^2 t \text{ , J/m}^2, \quad (4)$$

where ρ– the water density, kg/m^3; V – the velocity of raindrop fall, m/s; I_{rain} – the rain intensity, m/s; t – rainfall duration, s. The determination of the raindrop size and the fall velocity of raindrops have been described earlier [5]. The equation (4) is suitable for the rainfall created by simulators applied in both experiments. There is a dependence between A and AI:

$$AI(\text{t-m/ha}) = 2.3 \cdot 10^4 \text{A (J/m}^2). \quad (5)$$

The equation (4) was used to calculate A_i for time moments (t_i) required to take the water volume and the equation (5) – for determining the AI_i value.

When obtaining the similar dependence between the soil infiltration capacity and the erosion index of rain by using two different rain simulators, it seemed reasonable to conclude that the portable simulator may find an application for assessing this dependence. However, it is necessary to take into consideration that the above experiments contain 4 sources of uncertainties (errors):

1. The difference between the properties in two soil monoliths taken for the laboratory experiment is not known;

2. It is impossible to measure exactly the beginning of the runoff;

3. The rainfall intensity was measured at the beginning and the end of experiment. Its behavior between these measurements is unknown. In view of this, the initial rain intensity was used to assess the dependence between K_i and AI_i , whereas the minimal infiltration velocity K_{min} was determined by the final rain intensity;

4. It is not known how close is the infiltration intensity to its minimal state at the end of experiment.

RESULTS AND DISCUSSION

To detect the rainfall intensity, the water volume was taken in 10 replications: Δt_i = 20 s for the large rainfall simulator and Δt_i = 60 s for portable one. At first, the water volume was taken continuously, thus permitting to take into complete account the whole rain runoff. Further on, when the increase in water discharge became slowly there were intervals in 5 min. To determine only the volume of water the soil particles were removed by filtration. The experimental results are presented in Table. Fig. 3 demonstrates the dependence of infiltration intensity on time. When the rain intensity was constant the surface runoff increased striving to maximum. This means that the soil is capable to infiltrate a definite water volume, the other rain water flows through the soil surface that is why the infiltration intensity indicated in Fig. 3 is the soil infiltration capacity, i.e. $K(t) = I_{\text{inf}}(\text{t})$. The initial rain intensity was taken as equaled to K_{kp} and used for calculating the I_{inf} by means of equation (2) but $A(t_i)$ using the equation (4). The final rain intensity was applied for calculating the minimal infiltration capacity K_{min}. Strictly speaking, it is necessary to have the similar rain intensities (the higher is the difference between them, the greater is the error in obtained experimental data). For instance, in case of using the large rain simulator the final infiltration intensity seemed higher as compared to that at the beginning of the runoff. The equation (2) shows that $K_{min} > I_{inf}, t$, being averaged as $K_{min} = 2.6\ I_{inf}$.

As seen from Table, the K_{min} value was the same in both experiments. Fig. 4 shows the dependence between the infiltration intensity (the soil infiltration capacity) and the erosion index of rain $AI(t)$. In the experiment with the large rain simulator at $AI > 75$ t-m/ha the calculated infiltration intensity (the right line in Fig. 4) is higher as compared to the measured one. This is explained by the fact that the rain intensity at the end of experiment (1.67 mm/min) proved to be higher than that at the beginning of experiment (1.54 mm/min). The ratio between the maximal time before the beginning of the runoff and its minimum makes up 3.5/1.5 = 2.3 being equaled to 8.8/6/7 = 1.3 for AI_{kp}. Bearing in mind a relative uncertainty in determining the runoff beginning, one should notice that the AI_{kp} values were very close to each other in these experiments. The maximal AI value was equal to 113 t-m/ha in case of the large rain simulator, and 225 t-m/ha in the experiment with portable rain simulator. It is worth emphasizing that the maximal AI value made up 87 t-m/ha for natural rainfall recorded during the last 30 years in Nizhnedevitskaya water-balanced experimental station in the Voronezh region [5]. Having used the rain simulator, it is feasible to create such erosion-dangerous rains which haven’t been recorded earlier.

Thus, it seems reasonable to conclude that the dependence of the soil infiltration capacity determined by a portable rainfall simulator was close to that detected by the large rain simulator. Hence, the rill erosion has no influence (or has a small influence) on the soil infiltration capacity.

This affirmation should be explained by the following way. Under natural conditions the catchments reveal a network of small channels where water runoff concentrates and the area covered by this network of channels accounts for a small share from the total catchment area. It leads to the following conclusion: the water volume in runoff is not dependent on construction of the channel network. The water run- off

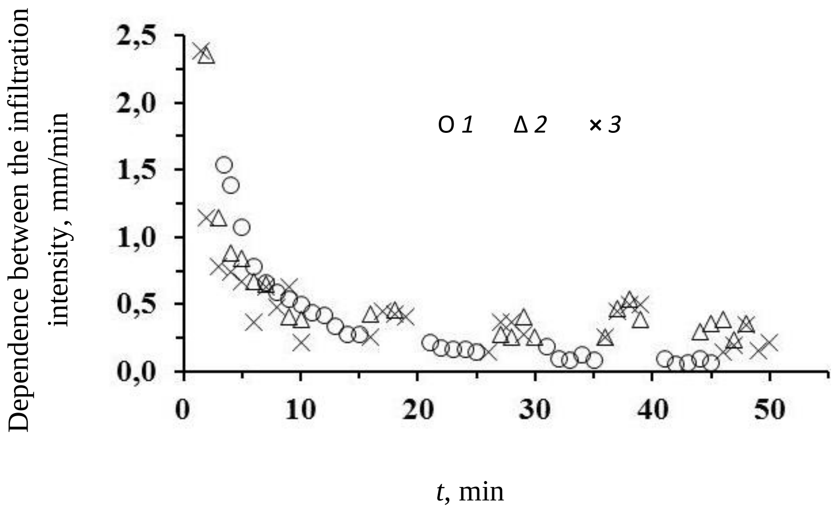

Fig. 3. The dependence of infiltration intensity (soil infiltration capacity) on time: *1* – large rainfall simulator, *2* – portable rainfall simulator (the first replication), *3* – portable rainfall simulator (the second replication).

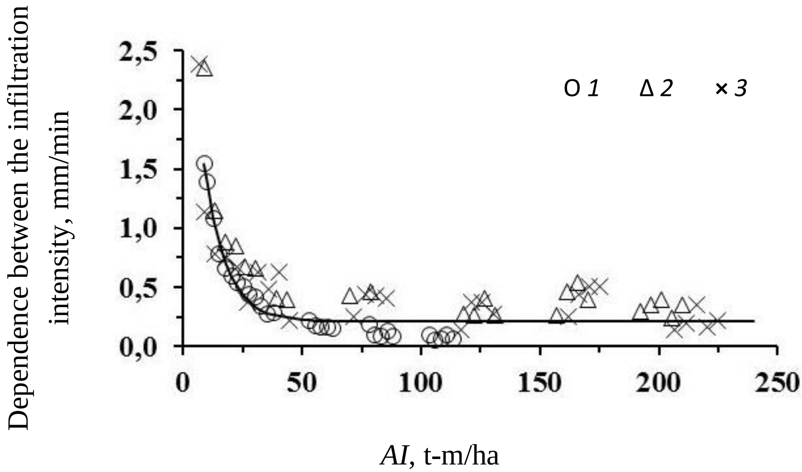

Fig. 4. The dependence between the infiltration intensity (soil infiltration capacity) and the erosion index of rain *AI*(*t*); *1* – large rainfall simulator, *2* – portable rainfall simulator (the first replication), *3* – portable rainfall simulator 9 the second replication), a right line – calculation by using the equation (*3*) in experiment with the large rainfall simulator.

depends predominantly on the soil infiltration capacity, from the surface of which the rain water flows down the channels. This is evidenced by SCS equation (Soil Conservation Service in the USA) in which the run-off layer of rain water is not dependent on the form and area of the catchment [9]. The application of the above equation was tested for conditions in Central Chernozem zone of the Russian Federation [3, 4].

CONCLUSION

The portable rain simulator can be applicable for assessing the soil infiltration capacity, thus decreasing expenditures for experiments to a considerable extent. However, further studies are needed to perfect the methods for experiments with this rain simulator.

REFERENCES

1. Vytovtov V.A., Sukhanovskii Yu.P., Pruschik A.V., Sanzharova S.I. *Laboratory and field* rainfall simulator. RF Patent number 2417578, 2011.
2. Vytovtov V.A., Sukhanovskii Yu.P., Sanzharova S.I., Pruschik A.V., Solovyov YA *Portable laboratory and field* rainfall simulator. RF Patent number 2519789, 2014.
3. Sukhanovskii Yu.P. Probabilistic Approach to the Calculation of Soil Erosion Loss, *Eurasian Soil Science*, 2013, Vol. 46(4), pp. 431–437. DOI: 10.1134/S1064229313040133.
4. Sukhanovskii Yu.P. The dependence of the infiltration rate on the rain erosivity index, *Eurasian Soil Science*, 2003a, Vol. 36(10), pp. 1114–1123.
5. Sukhanovskii Yu.P.Modification of a rainfall simulation procedure at run-off plots for soil erosion investigation, *Eurasian Soil Science*, 2007,Vol. 40(2), pp. 195–202.
6. Sukhanovskii Yu.P., Ollesch G., Meissner R., Rode M., Khan K.Yu., Volokitin M.P., Son B.K. Applicability of the Universal Soil Loss Equation for European Russia, *Eurasian Soil Science,* 2003b, Vol. 36(6), pp. 658–663.
7. Sukhanovskii Y.P., Ollesh G., Khan K.Y., Meisner R. A new index for rainfall erosivity on a physical basis, *J. Plant Nutrition Soil Science*, 2002, Vol. 165, pp. 51–57.
8. Wischmeier W.H., Smith D.D. Predicting rainfall erosion losses, *Agricultural handbook,* No. 537. Washington. 1978. 65 p.
9. Young R.A., Onstad C.A., Bosch D.D., Anderson W.P. *AGNPS, Agricultural Non-Point-Source Pollution Model. A Watershed Analysis Too*l. U.S. Dept. of Agr. Conservation Research, Report 35, 1987, 80 p.
10.Zingg A.W. Degree and length of land slopes as it affect soil loss in runoff, *J. of Agric. Engineers*, 1940. V. 21(2), pp. 59–64.