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Model of Artificial Sprinkling to Study the Influence of Slope Steepness and Rainfall Rate on Soil Erosion

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ABSTRACT

Water erosion of soils is an example of soil degradation problem in the mountainous areas of the Republic of Uzbekistan. The Republic of Uzbekistan is located in the Central Asian region, in the interfluve of the Amu Darya and Syr Darya rivers and has a unique combination of flat and mountainous terrains. Of the total area of the Republic (44.884 million hectares), mountains and foothills occupy an area of 13.429 million hectares (including rocky soils), which is 29.9% of the total territory. The natural conditions of the mountainous areas of Uzbekistan create a potential risk of soil erosion. Largely, the reasons for its manifestation are natural factors (rainfall, irregularity of surface relief), and anthropogenic factors (improper land use, failure to comply with the requirements for soil protection). The research aims to assess the condition of eroded soils in mountain and foothill areas based on models that consider natural factors (slope steepness and rainfall rate). During the research, the authors developed a model device for artificial sprinkling. Experiments under conditions of artificial sprinkling were conducted on soil monoliths prepared to determine soil washout at a rain rate of 2-4 mm/s, an experiment duration of 20 minutes, and a change in slope steepness by 5, 10, 15, and 20 degrees. The article presents the results of determining the time of soil washout on different slopes under conditions of artificial sprinkling, the amount of soil washed away, the time the soil began to wash out, and the depth of water penetration and wetting of the soil profile monolith.

Keywords: erosion, soil, washout, slope steepness, rainfall.

INTRODUCTION

Soil erosion is a critical environmental problem in almost land ecosystems worldwide. Erosion causes serious damage to crops, pastures, and other natural ecosystems (Zuazo & Pleguezelo, 2008). Soil erosion is a natural process enhanced by human activities and natural factors and occurs in all landscapes and under different types of land use (Mitasova, 1997; Bakker, 2005). Since the mountainous area is devoid of special direct impacts of anthropogeny, the main factors causing soil erosion are natural: intense rainfall and morphometric characteristics of the earth's surface. According to statistics, in India, about 6.6 billion tons of soil per year are washed away due to water erosion (Lal, 1990), and in China, the amount of washed away soil is approximately 5.5 billion tons (Wen, 1998). Many authors have addressed the issue of water erosion using various models (Wen, 2023; Xu, 2022). An important indicator that determines erosion processes is the terrain. The steepness and exposure of the slope play an important role in the formation of mountain soils, defining the basic properties of soils while having a primary impact on the formation of zonal characteristics. Landscape features influence soil properties (Moore, 1993), vegetation distribution (Frank, 1986), runoff and moisture content in soils. In particular, erosion reduces water-retaining capacity due to rapid water runoff and reduces the amount of organic matter in soils (Zuazo & Plequezelo, 2008).

Climate, like topography, is the most important factor on which soil erosion depends. Climatic factors directly affect water erosion, which forms surface runoff and soil loss. As we know, the impact of raindrops and surface water flow can cause erosion (Wei, 2007). Water erosion caused by excessive rainfall is recognized as one of the most common types of soil erosion, significantly affecting about 751 million hectares of land worldwide (Lal, 2004).

Mountain areas are characterized by extremely diverse climatic conditions due to large vertical extent and dense and deep dissection of the territory. As a result of a review of the literature sources, data were obtained on higher surface runoff at a 2 to 6 times increase in precipitation and even higher washout of soil products (Kocherga, 1966). The rate of water erosion is determined by the size of raindrops, which break up soil particles, thereby increasing soil density and reducing soil permeability, which leads to the dispersion of soil particles and washing water fractions out of soil pores (Zaslavsky, 1979).

Many scientists have been interested in the relationship between the rate and duration of rainfall, and relief conditions (steepness and aspect of the slope) on the terrain, especially from the point of view of severe soil erosion (Panagos, 2015; Guzzetti, 2008), numerous studies have been conducted based on various models (Cohen, 2004; Demirci, 2012; Ganasri, 2016). The most conventional models for the research of soil erosion are the models of "Universal Soil Loss Erosion Equation" (USLE) and "Revised Universal Soil Loss Equation" (RUSLE) (Renard, 2002; Afaf, 2017; Atoma, 2020).

Good results were obtained using artificial sprinkling models applied in soil erosion studies (Prushchik, 2019; Sobol, 2015; Demidov, 2016; Sukhanovsky, 2017). The conditions for artificial sprinkling of soils are based on the same mechanical laws as conventional rainfall but the processes of soil washout, erosion, and sedimentation differ significantly. The differences lie in that, first, under natural conditions, the origin of water flow is formed by precipitation (rate and duration), and second, in the difference in the water flow formation.

MATERIALS AND METHODS

For the first time, an artificial sprinkling model was used in Uzbekistan's mountainous regions to study erosion processes. Soil monoliths were prepared for the laboratory experiment. Soil monoliths were prepared for the laboratory experiment. The authors of the article created the artificial sprinkling device. This device received copyright certificate No. 006707 from the State Agency "Intellectual Property Center" under the Ministry of Justice of the Republic of Uzbekistan. The model of the artificial sprinkling device has a plastic tank with a capacity of 200 liters of water, filled with water through a simple polyethylene hose. The water in this tank is supplied to the sprinklers through polyethylene pipes designed to convey water. The rain control valve (faucet) determines the water flow rate, that is, it sets the amount of rain at a given rate. Excess water flows from polyethylene pipes into a wastewater tank. Water from the drainage pipes completely covers the area irrigated by the sprinklers, i.e. soil monolith. When the rain rate is controlled by the rain control valve, the amount of water used is determined by the water consumption meter. It should also be noted that the device is equipped in such a way that using the lifting levers we can create an artificial slope of the desired steepness. Therefore, the simulated rate of artificial precipitation and the simulated steepness of the slope on which the soil monolith is located can simulate water erosion. In the process of artificial sprinkling, washed-off soil from the top layer of the soil monolith falls through a tray for dumping washed soil onto a sieve collector for washed soil, equipped with filter paper. Excess water in the sieve goes into the sewer container, and the washed-out soil remains on the filter paper (**Figure 1**).

Figure 1: Laboratory device “Model of artificial sprinkling”

During the research, soil monoliths were prepared to determine soil loss under artificial irrigation conditions. The selection of monoliths was conducted depending on the type of soil and the degree of soil erosion (Table 1).

Table 1: Indices of monoliths prepared for the experiment

Monolith No.	Degree of erosion of the soil monolith	Slope steepness, °C
M-1	I – Alluvial, accumulative zone	A- 5
M-1	II - watershed	B-10
M-1	III – eroded transit zone, slope	C-15
		D-20

All experiments were conducted in 3 repetitions and then averaged. At each repetition of the experiment, the sieves with filter paper to catch the washed soil were changed. The soil remaining on the filter paper was dried, and its mass was weighted using an electronic scale.
In the experiments, the rain rate was set at 2.4 mm/s, and the experiment lasted up to 20 minutes. The experiments were conducted at slope steepness values of 5, 10, 15, and 20 degrees. The height of a raindrop fall was from 60 cm to 1 m depending on the slope, and the diameter of the drop was 2.4 mm.

RESULTS AND DISCUSSION

The Republic of Uzbekistan is located between the Amu Darya and Syr Darya rivers and occupies an area of 448.9 thousand km^2. The length of the territory from west to east is 1,425 kilometers, from north to south - 930 kilometers. The territory borders Kazakhstan in the north and northeast, Kyrgyzstan and Tajikistan in the east and southeast, Turkmenistan in the west, and Afghanistan in the south. The total length of the state border is 6221 kilometers. The border length with Afghanistan is 143 km, with Kazakhstan - 2,356.31 km, with Kyrgyzstan - 1,476.12 km, with Tajikistan - 1,283.2 km, and with Turkmenistan - 1,831.49 km. The mountainous region occupies the eastern part of Uzbekistan. Some ridges extend far to the west into the area of ancient alluvial plains. The experiments were conducted on monoliths prepared from dark gray soils common in the Baysun mountain range in the Surkhandarya region of the Republic of Uzbekistan.

The soils (their mechanical composition) of the object under study are classified as heavy, medium, and sometimes light loams. The reason for this is that the soils are distributed over different elements of the slope and are eroded to varying degrees. It was noted that the soils common in the watershed and alluvial part of the region are predominantly heavy loamy ones, and on slopes of high steepness - medium and light loamy soils. At the same time, as a result of "claying" and washout due to erosion processes in soils common in mountainous areas, the mechanical composition of the upper layers is lighter, and if the soil profile contains a lot of silty and fine sand and dust fractions, then these soils are more resistant to erosion.

According to the experimental results, it is seen that the mass of washed-away soil increases with an increase in the slope steepness. For example, in monoliths M-1.III, M-2.III with a rainfall rate of 2 mm, at a slope steepness of up to 5°, 0.5696 t/ ha was washed away; at a slope steepness of 10°, 0.7250 t/ha was washed away; at a slope steepness of 15°, 1.0634 t/ha was washed away; and at a slope steepness of 20°, the amount of washed away soil was 1.5741 t/ha. With a rainfall rate of 4 mm, these values were 0.700 t/ha at 5°, 1.0946 t/ha at 10°, 1.4589 t/ha at 15°, and 1.7705 t/ha at 20°. This situation is characterized by the location of the soil site, that is, an increase in the thickness of the humic layer depending on which elements of the slope are considered, a decrease in silt fractions in the mechanical composition, compaction of the structure, a change in structure, an increase in the water-resistant nut-like structure, a deeper location of the carbonate layer, that is, an increase in soil erosion resistance (**Table 2**).

Table 2: The influence of slope steepness in the formation of soil erosion under artificial sprinkling conditions

Monolith No.	Rain rate, mm/min	Amount of washed away soil, t/ha			
		Slope A-5°	Slope B-10°	Slope C-15°	Slope D-20°
M-1.I		0.3982	0.6571	0.8241	1.4089
M-1.II	2/20	0.5241	0.6679	0.9268	1.4607
M-1.III		0.5696	0.7250	1.0634	1.5741
M-2.I		0.5188	0.8866	1.2830	1.5295
M-2.II	4/20	0.5464	0.9330	1.3313	1.5411
M-2.III		0.7000	1.0946	1.4589	1.7705

One of the important indices of rain when erosion occurs is the time it falls since the danger of rain at the same rate at different periods differs and the course of this process depends on the vegetation cover and soil conditions. It is known that vegetation protects soils from erosion processes, and when this ability decreases, that is, when the vegetation is scarce, the soil becomes less resistant to erosion.

According to the hydrometeorological data of the object under study, it was noted that the average long-term (2010-2020) amount of precipitation fell in the spring and winter months. If to consider this by years, the greatest amount of precipitation fell in the spring months of 2020 - 449.7 mm (**Figure 2**).

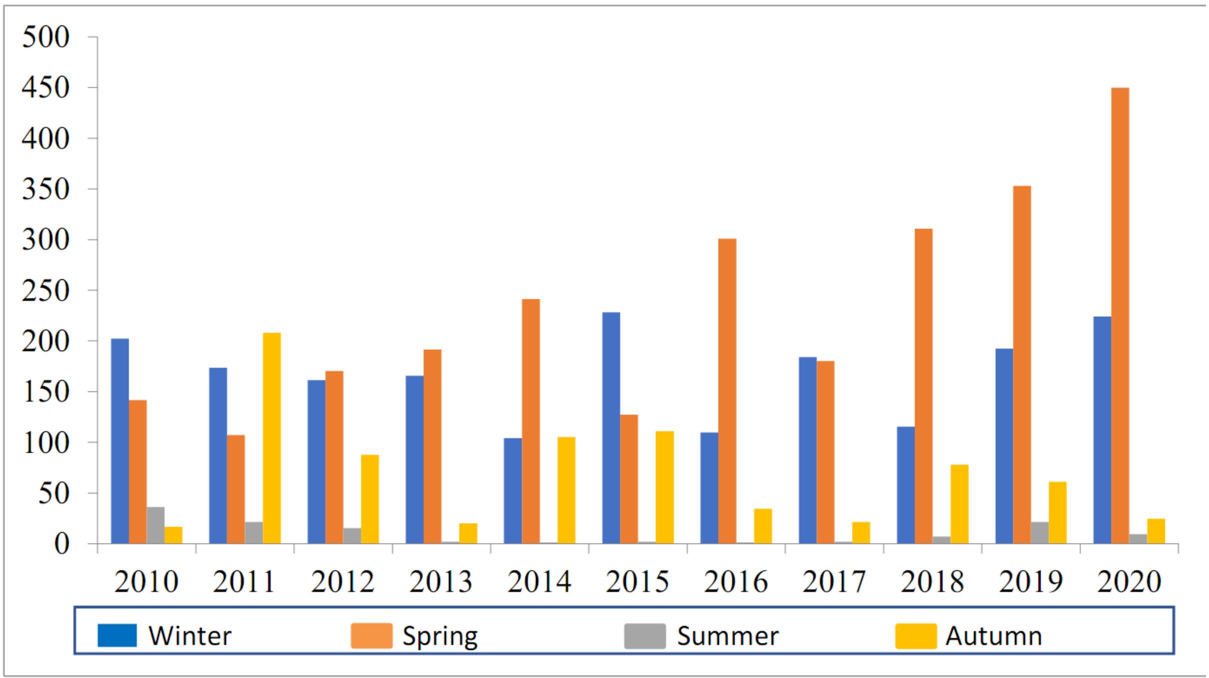

Figure 2: Average long-term (2010-2020) precipitation in the object under study (mm)

The threshold value for the diameter of raindrops when washing away soil is 0.2–0.8 mm. Generally, droplets up to 1.5mm in diameter cause slight disturbance of the topsoil and slight stirring of the topsoil by runoff caused by rainfall. Drops with a diameter of 1.5 to 3.0 mm cause severe disruption and disintegration of the structure of the top layer of soil, and compaction of the topsoil. When drops of this diameter fall on the soil, a poorly permeable crust forms on the top layer of soil after the soil dries. At the same time, even if the rainfall rate is the same but the drop diameter is different, a special situation is observed, for example, with a raindrop with a diameter of 2.5 mm, soil loss occurs 5 times faster than with a drop with a diameter of 1.4 mm (Bredikhin, 1989; Egorov, 2015). The classification indices of raindrops in the formation of erosion processes are given in **Table 3**.

Table 3: Classification indices of raindrops in the occurrence of erosion processes

Raindrop diameter, mm	Energy of one raindrop, J	Characteristics of erosion processes
Less than 0.2	Less than $1.1 \cdot 10^{-9}$	There is moderate and uniform soil wetting
0.2 - 0.8	$1.1 \cdot 10^{-9}$ - $1.4 \cdot 10^{-6}$	There is slight stirring in the top layer of soil with small streams of water
0.8- 1.5	$1.4 \cdot 10^{-6}$ - $2.6 \cdot 10^{-5}$	There is a slight disturbance in the top layer of soil; water flows slightly stir the top layer.
1.5 - 3.0	$2.6 \cdot 10^{-5}$ - $4.7 \cdot 10^{-4}$	The top layer of soil is severely disturbed, scattered, and compacted
More than 3.0	More than $4.7 \cdot 10^{-4}$	There is a very strong disturbance of the soil structure, saturation of fine soil runoff

The diameter of raindrops depends on the intensity of the falling rain. For example, if the rain rate is 0.02 mm/s, then the diameter of the raindrops is 0.6 mm, if the rain rate is 1-2 mm/s, then the diameter of the raindrops varies within 2-3 mm, and when it rains at a rate of above 4 mm/s, the size of raindrops exceeds 4.5 mm. Generally, erosion processes are not observed during rain of low rate and at a small diameter of raindrops.

Observations during the experiments showed that in dark gray soils with a slope steepness of 5° and with a rain duration of 20 minutes, with a rate of 2 mm, soil washout begins after 5 minutes 08 seconds, and the depth of water penetration and wetting of the monolithic soil profile is 41 mm, which is 0.3982 t. Soil loss was also observed. When this amount of precipitation is maintained, with a slope steepness of 10°, 15°, 20°, the time for the onset of soil loss decreases, and the mass of washed-away soil increases (**Table 4**).

Table 4: Indices of the influence of precipitation rate on the formation of soil erosion under artificial sprinkling conditions

No. of monolith	Start of soil washout time, min/sec	Depth of soil profile wetting, mm	Amount of washed out soil	
			gr	t/ha
		Rain rate 2/20 mm/min		
M-1.I-A	5.08	41	4.46	0.3982
M-1.II-A	5.06	41	5.87	0.5241
M-1.III-A	5.0	41	6.38	0.5696
M-1.I-B	4.41	38	7.36	0.6571
M-1.II-B	4.38	38	7.48	0.6679
M-1.III-B	4.35	37	8.12	0.7250
M-1.I-C	4.15	32	9.23	0.8241
M-1.II-C	4.13	32	10.38	0.9268
M-1.III-C	4.09	30	11.91	1.0634
M-1.I-D	3.42	26	15.78	1.4089
M-1.II-D	3.39	25	16.36	1.4607
M-1.III-D	3.37	24	17.63	1.5741
		Rain rate 4/20 mm/min		
M-2.I-A	4.48	38	5.81	0.5188
M-2.II-A	4.42	38	6.12	0.5464
M-2.III-A	4.31	37	7.84	0.7000
M-2.I-B	4.28	39	7.42	0.6625
M-2.II-B	4.13	38	7.61	0.6795
M-2.III-B	4.03	36	8.83	0.7884
M-2.I-C	3.54	34	9.86	0.8804
M-2.II-C	3.48	32	10.52	0.9393
M-2.III-C	3.42	31	12.74	1.1375
M-2.I-D	3.34	29	14.56	1.3000
M-2.II-D	3.27	27	15.13	1.3509
M-2.III-D	3.16	26	17.71	1.5813

CONCLUSION

Experiments under artificial sprinkling conditions were conducted on soil monoliths prepared to determine soil washout at a rain rate of 2.4 mm/s, an experiment time of 20 minutes and a change in slope steepness by 5, 10, 15, and 20 degrees. In dark gray soils with a rainfall rate of 2 mm, at a slope steepness of 5°, 0.5696 t/ha of soil was washed away, 0.7250 t/ha at 10°, 1.0634 t/ha at 15°, and 1.5741 t/ha at 20°. These values were 0.700 t/ha at 5°, 1.0946 t/ha at 10°, 1.4589 t/ha at 15°, and 1.7705 t/ha at 20° and; the same pattern was observed in mountain brown soils. As was noted above, the main natural factors that determine the rate of erosion processes are climatic conditions (amount and rate of rainfall, etc.), steepness, and exposure of slopes. With an increase in the steepness of slopes and the rate of rainfall, the kinetic force of raindrops increases, as a result, the soil is quickly washed away, the permeable pores become clogged, the water permeability of soil decreases, and its tendency to be washed away increases.

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