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The Effect of the Degree of Slope and Rainfall Characteristics on Runoff and Soil Erosion

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TABLE OF CONTENTS

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The Effect of the Degree of Slope and Rainfall Characteristics on Runoff and Soil Erosion

JESSE H. NEAL*

INTRODUCTION

The factors affecting soil erosion are so many and so varied that it is difficult to determine the relative importance of each individual factor, especially under natural conditions. Even on small areas the soil varies widely in its physical characteristics and conditions, and in its ability to produce vegetation. Rainfall characteristics are so varied that the erosion caused by one rain can seldom be compared with that produced by another. The moisture condition of the soil at the time of a rain, the soil structure, the surface condition and the vegetative covering are continually changing.

To determine the effect of any one factor, the other factors must be held constant or measured, while the variable being studied is altered by definite increments. It is the purpose of this paper to present the results of a study of a few factors affecting erosion which were obtained by setting up a miniature laboratory-controlled field on which the degree and length of slope, the rainfall intensity and duration, and the soil conditions were regulated or measured. The experiment was set up to study the effect of the degree of slope and rainfall characteristics on runoff and soil erosion from a cultivated field by varying one factor at a time and keeping all others as nearly constant as possible. Rainfall intensities of 0.90, 1.50, 2.00, 3.00, and 4.00 inches per hour were maintained within 0.20 inch of the required amount. The slope was varied usually by geometric progression between 0 and 16 per cent.

Since artificial rain was used in conducting these experiments, it was important to compare its characteristics with natural rain, especially in regard to the sizes and velocities of their respective drops. In the first part of this paper, therefore, a discussion of the impact of falling drops of water is presented. The second part deals with runoff and soil losses under different conditions of rainfall, slope and soil.

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REVIEW OF LITERATURE

The characteristics of rainfall are discussed at considerable length by Bentley (7). He devised a unique method of measuring the sizes of the drops by catching them in a tray of smooth, sifted flour which was exposed to the rain for one or two seconds depending upon the intensity of the rainfall. By experiments with artificial rain, he found that the size of the dough pellets formed in the flour corresponded very closely to the size of the drops of water producing the pellets. These pellets were dried, measured and photographed. He obtained 344 sets of raindrop impressions from 70 different storms, and at different times during an individual storm.

He observed that clouds moving in horizontal strata either high or low seldom precipitate large drops, but that clouds moving in vertical planes (typical of thunderstorm clouds) usually form large drops.

The sizes of raindrops received from different kinds of clouds were as follows:

	Size of raindrops in mm.				
	<1.0	1.0-1.6	1.6-3.4	3.5-5.0	>5.0
Kind of clouds	Per cent of total no. drops.				
Low-lying clouds[1]	6.8	10.0	7.0	1.7	0
Combination of high and low clouds	10.2	21.6	21.6	15.6	4.3
High-lying clouds[2]	0.4	0.6	0.3	0	0

[1]Cumulus, nimbus or low stratus, cirro-stratus, and combination of cumulus and nimbus.
[2]Cirro-cumulus.

Although a greater number of the raindrops are small, the major portion of the rainfall comes in medium to large drops, since their volume varies as the cube of their diameters.

The rain which falls is taken up by infiltration into the soil, is held in depressions, or is lost as runoff.

Horton (17) has made an extensive study on rates of infiltration under different soil, watershed, rainfall and climatic conditions. He defines the infiltration capacity as the rate at which a given soil can absorb rainfall. This capacity varies between a maximum value when the soil is dry and a minimum value when the soil is thoroughly wet and packed by rain. The infiltration capacity decreases rapidly after the beginning of a rain due to the following causes:

1. Packing of the surface by rain
2. Swelling of the soil

3. In-washing of fine material into the soil openings

After the rain ends, the maximum infiltration capacity is soon restored by (a) wind action, (b) differential temperature, (c) shrinkage of colloids, (d) penetration of earth worms and insects.

Horton gives the following methods for determining the infiltration capacity.

1. By laboratory experiments, using artificial rainfall
2. From runoff-plot experiments, with natural rainfall
3. From rainfall and runoff records for small drainage basins with homogeneous soils
4. By the average equivalent infiltration capacity for a drainage basin

He also found a marked *seasonal* variation in infiltration capacity. For one series of tests, the average infiltration during summer storms was 0.99 inch per hour, while for winter storms (November to April) the average was only 0.12 inch per hour.

Musgrave (24) studied the rate of infiltration (a) in lysimeters of normal soil 3 feet in diameter and 3 feet deep, (b) in 6-inch cylinders, 8 to 18 inches long, which were forced into the soil by means of jacks, and (c) by comparing runoff and rainfall records for a given area. He found the results by the three methods to be in close agreement.

Musgrave and Free (25) reported results showing the effect (a) of increasing porosity by cultivation, (b) of crop covers, and (c) of variations in the initial moisture content of the soil on the rate and total infiltration. They found that the increase in pore space obtained by each additional inch of depth of cultivation significantly increased the infiltration. The increase of infiltration in Marshall soil due to any depth of cultivation was not significant after 30 minutes of rain, while in Shelby the effect was noticeable for 1½ hours. The rate of infiltration into the Marshall silt loam was about 7 times faster than into the Shelby loam. They conclude that close vegetation such as bluegrass or alfalfa does not increase the rate of infiltration as much as it retards the movement of water, thus giving more time for infiltration. Moreover there is less turbidity and less clogging of the pores. When there was a high initial moisture content of the soil, the infiltration was found to be very small.

Slater and Byers (29) compared the rates of percolation through open end cores of a highly erosive soil (Iredell silt loam) with those of a non-erosive soil (Davidson clay.) The rate of percolation through 14 cm. of Iredell soil was 0.03 inch per hour while the rate through 20 cm. of Davidson was 1.02 inch per hour.

The factors that influence the erosiveness of soils are classified by Baver (5) as (a) meteorological, (b) environmental, and (c) inherent. He summarized the factors affecting erosion by the following equation $(E)=f(R, G, V, S)$, in which E is amount of erosion, R is a factor depending on the amount and intensity of rainfall, G is a factor depending on the slope and area of the land. V is a factor depending upon the amount and nature of the vegetation. S is a factor depending on the physical properties of the soil.

He states that runoff is related primarily to the absorptive capacity of the soil and the permeability of the soil profile. The rate and amount of absorption increases as, (a) the texture of the soil becomes coarser, (b) the degree of granulation increases, (c) the content of organic matter and lime increases, and (d) the soil becomes looser. Not only must a soil absorb water to prevent runoff, but it must also permit the excess to percolate away. If the surface soil is pervious and the subsoil impervious, heavy rains are conducive to a large amount of erosion.

Relative to the factors responsible for granulation, Baver and Rhoades (6) found that soils high in organic matter contain from 15 to 30 per cent more granules than those low in organic matter and that the granules are three times more stable.

Yoder (33) states that the tendency of soils to break down from clods into smaller aggregates under the influence of moisture changes is one of the most significant dynamic properties of soils in relation to erosion control and tillage practices.

Middleton (22) studied the physical and chemical properties of erosive and non-erosive soils and found that the dispersion ratio was the most valuable single criterion. He determined the erosion ratio by dividing the dispersion ratio by the ratio of colloid content to moisture equivalent. He classified soils with an erosion ratio of less than 10 as non-erosive.

Bouyoucos (8) prefers the clay ratio $\frac{(\text{sand} + \text{silt})}{\text{clay}}$ as a criterion for judging the relative erosiveness of soils instead of the dispersion or erosion ratios.

To study the effect of slope on erosion several investigators have used a soil tank filled with soil placed in homogeneous layers or strata in the same order as taken from the natural soil. Lowdermilk (19) placed the soil in a galvanized iron tank 2 feet by 5 feet and 2.5 feet deep. The soil was underlaid by a stratum of sand and gravel to collect and drain out the percolation water. The slope was set at 30 per cent. Artificial rain was applied through a sprinkler pipe over each side of the tank with No. 2 nozzles spaced 2 feet apart in each pipe but staggered so as to throw a jet of water every foot.

Duley and Hays (14) placed the soil in a larger tank, 2 feet by 10 feet and 28 inches deep, and varied the slope by means of a hoist. The soil was placed in the tank in a similar manner to that employed by Lowdermilk. The water was applied manually by several sprinkling cans. The tests were started with the soil in a saturated condition.

They obtained a rapid increase in runoff as the slope was changed from 0 to 4 per cent, but as the slope was further increased to 20 per cent only a slight increase in runoff was obtained. The amount of soil lost increased very slowly as the slope was increased up to 3 or 4 per cent. Then with a further change in slope up to 20 per cent, the amount of soil lost increased very rapidly.

After a series of runs was made with a silty clay loam, the soil was replaced by a sandy loam and the tests were repeated. On the 8 per cent slope, the silty clay loam lost 158 per cent more soil than did the sandy loam, while on the 16 per cent slope the sandy soil lost 222 per cent more than did the silty clay loam. From these results, they concluded that it was difficult to classify soils as erosive or non-erosive on the basis of certain physical properties as was done by Middleton (22), unless the slope and rainfall characteristics were also considered.

In addition to the laboratory tests, Duley and Hays (14) made tests on field plots. The plots were laid out at different angles on the same slope to get a variation of slope on similar soils. The amounts of soil lost from the field plots, especially with the lighter applications of water and the flatter slopes, were not so consistent.

Nichols and Sexton (27) used field plots of 15 by 50 feet or $\frac{1}{58}$ acre ranging from a flat to a 20 per cent slope and applied the rain by overhead sprinklers. To insure uniformity of the soil, they removed all the surface soil and 6 inches of the subsoil which were thoroughly but separately mixed and then replaced. They found that the intensity of rainfall was more important than the amount in causing erosion. The rate of erosion varied as some power of the intensity. The kind of soil material lost also varied with different amounts and intensities of rainfall. The degree of saturation of the soil at the time of the rain affected (a) the absorption and, consequently, the erosion, and (b) the dispersion of the soil.

The results reported by Diseker and Yoder (16) were from the same plots described by Nichols and Sexton. These results were for both natural and artificial rain. The soil losses which they report do not vary as a power of the slope, when they plot soil loss against per cent of slope; one curve is S-shaped and the others are approximately straight lines.

Chapline (11) reports the effect of vegetative covering on range lands. When the vegetative cover was increased from 16 to 40 per cent, the runoff from summer rains was reduced 55 per cent and the soil loss was reduced 56 per cent.

Weaver and Noll (31) report on the effect of different cultural practices on runoff and soil losses for both natural and artificial rain. Both runoff and soil losses increase with change in cultural practice in the following order: prairie meadow, prairie pasture, wheat stubble, and fallow.

THE IMPACT OF FALLING DROPS OF WATER

Velocity of Falling Drops of Water

Before the impact of falling drops of water could be determined, it was first necessary to determine their velocity. Drops of water falling through a series of measured distances were timed by a stop watch. Drops of different sizes were let fall through distances of 3.5, 7, 14, 21, and 28 feet.

Since the time for a drop to fall through a short distance was too small to measure accurately with a stop watch, photographs of falling drops of water and drops of skim milk (specific gravity 1.04) were taken. This method was also used as a check on the stop-watch readings. The drops of water did not show up very clearly, but those of skim milk did. The drops were photographed with a 16 mm. moving picture camera and the pictures were thrown on a screen (turning a frame at a time by hand). The position of the drop on each frame was measured and recorded. Since the speed of the camera was set to take 64 exposures per second, it was possible to calculate the velocity of the falling drop.

The time required for drops of water and drops of skim milk to fall a given distance is given in Tables 1 and 2. There was a slight decrease in velocity with a decrease in size of drop. The relative velocities of the drops of water and drops of milk were in the ratio of their respective specific gravities.

TABLE 1.—TIME FOR DROPS OF WATER TO FALL A MEASURED DISTANCE

Volume of drop	Diameter of drop	Distance of fall		Time of fall	Velocity	Impact
cc.	mm.	feet	meters	sec.	M/sec.	gm.-cm.
0.147	6.5	3.5	1.067	0.40	2.67	39.2
.147	6.5	7.0	2.134	0.71	3.00	44.2
.147	6.5	14.0	4.267	1.02	4.18	61.5
.147	6.5	21.0	6.400	1.30	4.92	72.2
.147	6.5	28.0	8.534	1.70	5.02	73.7
.137	6.4	7.0	2.134	0.71	3.00	41.1
.137	6.4	14.0	4.267	1.02	4.18	57.2
.137	6.4	21.0	6.400	1.30	4.92	67.3
.051	4.6	7.0	2.134	0.72	2.96	15.1
.051	4.6	14.0	4.267	1.06	4.02	20.5
.051	4.6	21.0	6.400	1.39	4.60	23.4

TABLE 2.—TIME FOR DROPS OF MILK TO FALL A MEASURED DISTANCE

Volume of drop	Diameter of drop	Distance of fall	Time of fall	Velocity	Impact
cc.	mm.	meters	sec.	M/sec.	gm.-cm.
0.112	6.0	1	0.35	2.86	33.3
0.112	6.0	2	0.57	3.51	40.8
0.074	5.2	1	0.35	2.86	22.0
0.074	5.2	2	0.57	3.51	27.0

When the logarithm of the distance of fall was plotted as a function of the logarithm of time, a straight line was obtained (See Fig. 1).

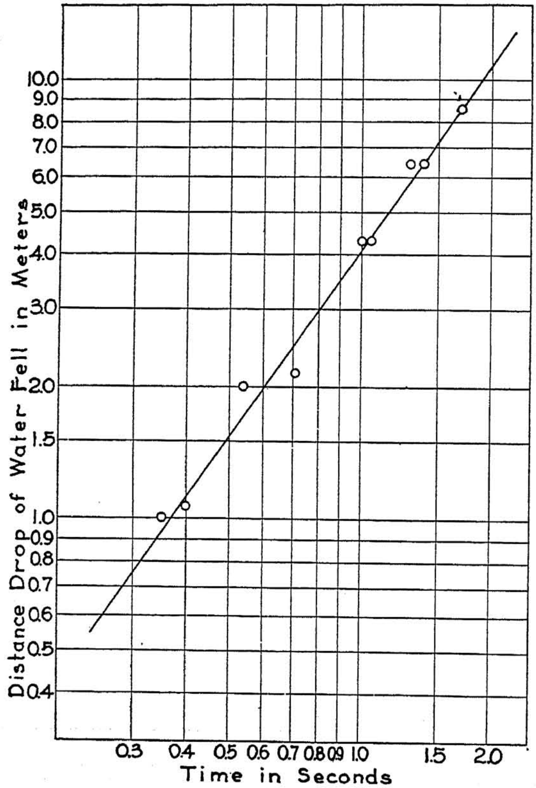

Fig. 1.—Distance a drop of water will fall in a given time.

The equation, determined graphically, giving the distance a drop of water would fall in a given time is as follows:

$$S = 4.1(t)^{1.425} \qquad (1)$$

where $S =$ distance in meters

$t =$ time of fall in seconds

From the above equation the acceleration of a falling drop of water was found to vary approximately inversely as the square root of the time. The greatest acceleration occurred during the first second of fall. After about two seconds from the time a drop had started to fall its acceleration became negligible; after this period it fell with a constant velocity.

Humphreys (18) states that "The maximum velocity in air of normal density.........., at which the larger drops break up, is about 8 meters per second."

The Impact of Falling Drops

The impactometer. An apparatus was constructed, as described by Neal and Baver (26), to measure and automatically record the impact of falling drops of water. (See Fig. 2.) It consisted of an analytical balance beam mounted between two steel point bearings. (Agate bearings would have been superior.)

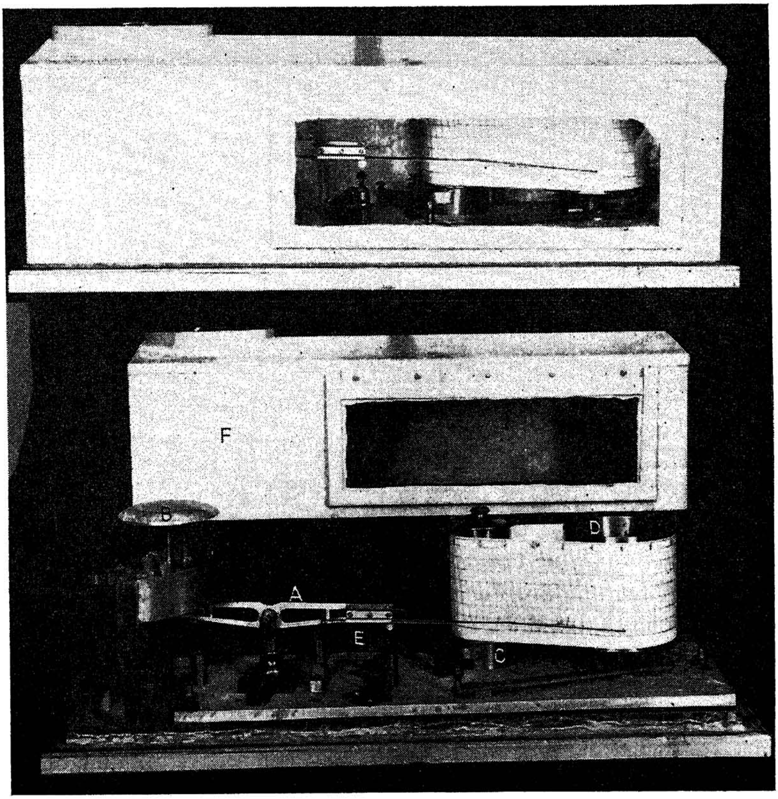

Fig. 2.—Apparatus for measuring the impact of raindrops: A, analytical balance beam; B, aluminum plate receiving impact; C, spring driving mechanism; D, clock regulating mechanism; E, spiral spring regulating deflection; F, metal cover.

By means of a steel stem screwed into the top of one end of the beam, a convex aluminum plate, 10 cm. in diameter, was mounted to receive the impact of the falling drops. A recording pen was attached to the other end of the beam. A capillary glass tube was used for the pen, the back end of which dipped into an ink well. The recording end was turned at a right angle to the direction of the beam, drawn to a point, and inclined slightly downward to facilitate the steady flow of ink.

The deflection of the pen resulting from the impact of rain drops on the plate was recorded on a chart on a drum which was driven by a spring and regulated by a clock. The length of the pen arm of the beam was about 3½ times that of the plate arm which magnified the deflection by that ratio. The magnitude of the deflection for a given impact was controlled by the elongation of a small spiral spring attached to the long arm of the beam.

The entire apparatus was enclosed in a metal case with an opening in the top to accommodate the plate. The plate rested about one cm. below the top of the case to prevent deflections due to wind movements. The runoff from the watershed of the plate was caught in a trough and carried outside the case through a pipe.

Measurement of impact. The impact of the raindrops is obtained by multiplying the mass in grams by the velocity of fall in centimeters per second. For comparative values of impact of artificial and natural rain see Table 1.

To calibrate the apparatus drops of water of determined mass were allowed to fall, through distances ranging from 1 to 5 meters, onto the plate of the impactometer. About ten drops were dropped from each height and the recording pen marked the deflection caused by the impact of each drop. The drops were timed far enough apart so that the recording pen returned to rest before the next drop struck. Each mark which the recording pen made above the base line was measured and the average deflection for each size drop was obtained. When one drop at a time fell, there was a close correlation between momentum (MV) and the deflection of the pen, but when several drops or a rain fell, there was a varying accumulation of water which made it difficult to maintain a constant base.

Due to a lack of time it was not possible to perfect the apparatus sufficiently to obtain accurate results on the relative impact of artificial rains owing to the fact that rust formed in the steel bearings. Moreover, complete provision for handling the accumulation of water on and under the plate of the impactometer could not be made. Further work is necessary to correct these experimental difficulties in the apparatus.

Significance of impact studies. The erosion of soils by water is, in part, a function of the rainfall characteristics. The beating action of falling rain drops upon the soil as well as the dispersive and cutting action of runoff water contribute to the loss of soil from unprotected lands. In studying the effect of rainfall characteristics upon erosion, it is essential to know what takes place when rain drops hit the soil. To understand thoroughly the significance of the resisting qualities of various soils and of different vegetative covers to erosion, it would be exceedingly important to be able to measure the impact with which rain strikes the soil under varying rainfall intensities. It would also be extremely valuable to compare the impact of artificial rains as employed in the following described experiments with the impact of natural rains of the same intensity.

EXPERIMENTAL PROCEDURE

Design and Construction of the Soil Tank

The soil tank was designed to give an area of the soil surface of 1/1000 acre and a depth of soil sufficient so that the runoff would not be influenced by too rapid percolation. It was made 12 feet long, 3.63 feet wide and 26 inches deep with the exception of the outlet and which was 24 inches deep. (See Fig. 3.) The tank was

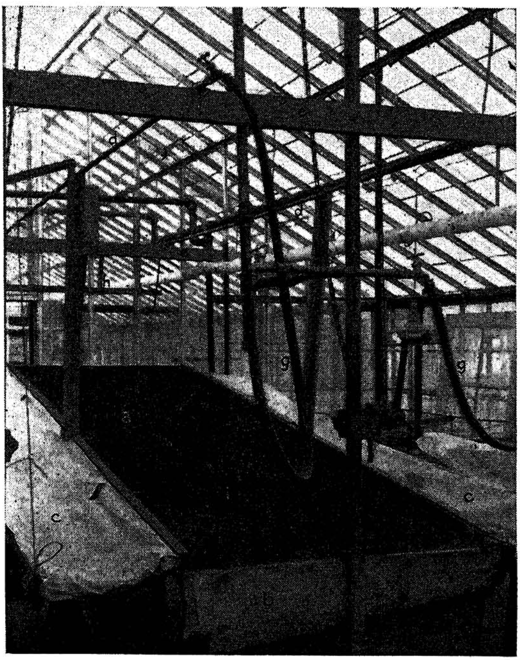

Fig. 3.—The experimental set-up: a, soil in tank as it was prepared for a run; b, trough to catch runoff; c, apron to catch overthrow water; d, sprinkler pipe; e, sprinkler pipe supports; f, down pipe from overflow supply tank; g, hose connection from supply tank to sprinkler pipe; h, oscillating lever; i, infiltration cylinders.

designed to carry a distributed load of 4 tons supported on a pivot one foot off the center. (See Fig. 4.) It was constructed of 2-inch plank. The sides were nailed to 2x4 inch cleats spaced every 3 feet. A $\frac{3}{8}$-inch tie rod extended across the tank 12 inches below the top at each pair of cleats. The joints and corners of the tank

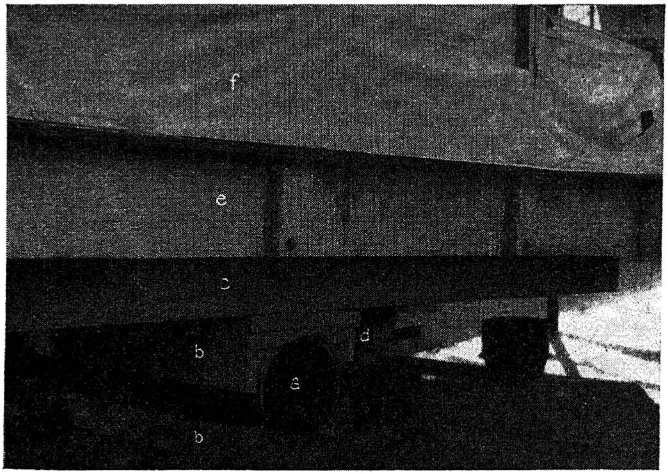

Fig. 4.—Details of soil tank construction: a, pipe on which soil tank was mounted; b, wooden bearings to give a greater bearing surface on pipe and to keep soil tank from slipping on the pipe; c, joists (four 2"x8") supporting soil tank; d, trough in which percolation water was caught and carried to one side; e, side of soil tank; f, apron to catch overthrow water, hanging along side of soil tank while not in operation.

were sealed with roofing mastic and asphalt paints. The outlet end was lined on the inside with a sheet of 28 gage galvanized iron which was bent out and down over the wood and then turned up at an angle to form a trough to catch and transport the runoff to one side.

The floor of the tank was made of 2x6 inch plank spaced $\frac{3}{4}$-inch apart and then covered with a $\frac{1}{4}$-inch mesh wire screen. Sheets of galvanized iron were placed under the floor boards and over the joists but bent down between the joists to form troughs to catch the percolation water. The edges of the sheet iron were turned up and tightly fastened to the sides of the tank. Near the outlet end, these troughs discharged into a trough set at right angles and under the joists which carried the percolation water to one side of the box where it was caught in a can.

Since it was desirable to have the tank set so that the slope could be changed with ease, it was mounted on four 2x8 inch fir joists which set on a 10-inch iron pipe as a pivot placed 5 feet from the outlet end. (See Fig. 4) To keep the tank from slipping on the pipe and to prevent the pipe from rolling, wooden bearings extending about ¼ the circumference of the pipe were used. A screw jack was placed under the heavy end of the tank to raise or lower it to the desired slope.

Preparation of Soil for Experiments

Physical characteristics of the soil. The soil used in this experiment was the surface 5 to 6 inches taken from a timothy meadow. It contained a large quantity of organic matter and small roots which held the soil particles in granules. Before the field had been seeded to meadow, it had suffered severe erosion. Only about 5 to 6 inches of the original surface soil were left. According to Baver (3, p. 45) the original surface soil of the Putnam series was 9 to 12 inches in depth.

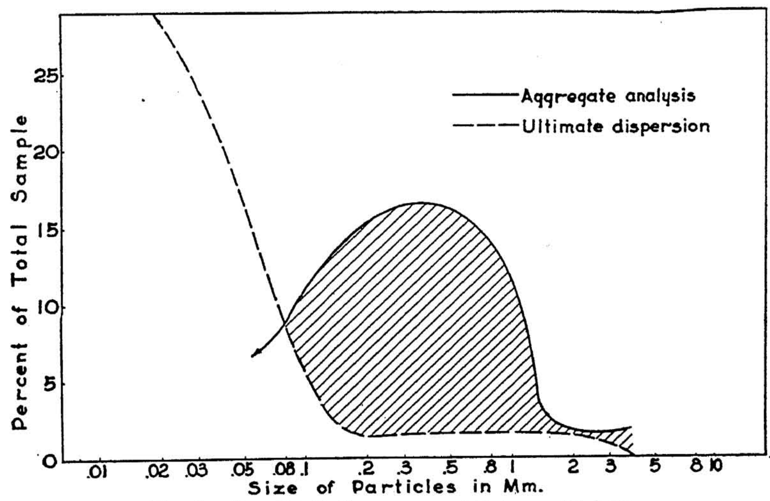

Fig. 5.—Size distribution curves of Putnam silt loam.

TABLE 3.—AGGREGATE AND ULTIMATELY DISPERSED ANALYSES OF PUTNAM SOIL

Size of particles	Untreated	Dispersed	Aggregates
mm.	per cent	per cent	per cent
>4	1.86	0	1.86
4-2	1.59	0.91	0.68
2-1	2.83	1.56	1.27
1-0.5	14.80	1.69	13.11
0.5-0.25	16.45	1.56	14.89
0.25-0.1	12.79	1.61	11.18
0.1-0.05 }		9.86	
0.05-0.005 }		27.33	
0.005-0.001 }	49.68	36.40	
<0.001 }		19.08	
Total	100.00	100.00	42.99

This soil was classed as a Putnam silt loam but had a higher degree of aggregation than most Putnam soils. (See Table 3 and Fig. 5.) Forty-three per cent of the particles smaller than 0.1 mm. were in aggregates larger than 0.1 mm. The physical characteristics of the soil are given in Table 4.

TABLE 4.—PHYSICAL PROPERTIES OF THE PUTNAM SOIL

Characteristic	Value
Apparent specific gravity (lb./cu. ft.)	78
Real specific gravity	2.3
Upper plastic limit[1] (% H_2O)	31.2
Lower plastic limit (% H_2O)	23.8
Plasticity number	7.4
Moisture equivalent (% H_2O)	23.7
Total pore space, per cent	45.6
Non-capillary pore space per cent	6.0
Organic matter content per cent	2.68

[1]By Troemner balance method described by Baver (see No. 1 bibliography).

After the infiltration tests were made as described on page 25 the cylinders containing the saturated soil were removed from the soil tank, cleaned, weighed, dried in an oven at 100°—110°C., and reweighed. From the weight of the soil in the cylinders, the maximum water holding capacity and the relative density of the soil were obtained.

The surface 10 inches had a relative density of 1.25 or 78 pounds per cubic foot. This was an average of three determinations which ranged from 1.23 to 1.27. The true specific gravity of the soil was 2.3.

This low value indicated a high organic matter content. The organic matter content, determined by the nitrogen method, was 2.68 per cent. The saturation capacity was about 35 per cent, while the capillary capacity was about 29 per cent. The capillary capacity was taken as the average moisture content 4 to 10 inches below the surface just before the irrigation or 24 hours after the previous irrigation.

Method of placing soil in tank. To insure drainage of the soil, a 6-inch layer of gravel and coarse sand was spread over the bottom of the soil tank. The ¼-inch mesh screen over the bottom prevented the gravel from falling between the floor planks.

The soil for the experiment was obtained when it had an optimum moisture content for working. It was mixed and put through a ½-inch mesh screen. While the soil was still in a moist condition, it was placed in the soil tank in increments of ½ to 1-inch layers. After each layer of soil had been added, it was worked into the layer below with a garden rake and packed by walking back and forth on the soil as it was worked. After the soil tank was filled to within 2 inches of the top or level with the outlet end, the soil was leveled off and wet down several times to get complete settlement before any erosion tests were made. About two weeks were allowed for settling.

Preparation of the soil for each run. Before each run the soil was dried and cultivated to a depth of 4 inches. As soon as the surface was dry enough, it was worked up with a garden rake. At the first working, the soil had dried only about a half inch deep. By frequent cultivations, the moist soil dried more rapidly. The depth of cultivation was increased as the soil dried, until a depth of 4 inches was reached.

After the moisture content of the surface 4 inches of soil had been reduced to between $\frac{2}{3}$ and $\frac{3}{4}$ of the capillary capacity, the surface soil was leveled off and worked down to approximately the proper height. Usually, additional amounts of soil were added after each run to bring the surface elevation back to the original height. This additional soil was taken from a reserve supply with a moisture content of about 50 per cent of the capillary capacity. It was worked into the surface soil so that it would not form a dry stratum. After the soil was approximately leveled off with a rake, a wooden templet was drawn the length of the box and all excess soil scraped off. Since the templet left the soil in a smooth condition, the rake was run lightly back and forth across the slope to simulate the condition of a good seed bed. The soil was left in this condition for two or three hours with a fan circulating the air over it. The surface inch of soil was further dried to between $\frac{1}{4}$ and $\frac{1}{2}$ the capillary capacity before applying the rain.

Soil moisture determinations. Just before each run, duplicate soil samples were taken with a core sampler at the following depths; 0-1, 1-4, and 4-10 inches. Similar samples were usually taken immediately after each run. The soil moisture content was determined on the basis of an oven dry soil.

Design, Calibration and Operation of Sprinkling System

Design. Since the rain was to be applied at a uniform rate, it was necessary to have a low constant pressure on the supply line. An adjustable overflow tank which could be set at pressure heads ranging from 0.5 to 5.0 feet was set above and a foot past the end of the soil tank so that the overflow water would not interfere with the tests. Water was run into the overflow tank fast enough to keep it overflowing at the required pressure head.

A 2-inch pipe extended about 5 feet down from the bottom of the overflow tank where a "T" reducer divided the water supply into two ½-inch pipes, each extending out about 15 inches. The sprinkler pipes were connected to the respective ends of the "T" by means of ⅝-inch hose. The hose permitted flexibility in the oscillation and longitudinal movements of the sprinkler pipes which will be discussed later. A globe valve was inserted on each line where the hose connected with the iron pipe. (See Fig. 3.)

The water was applied through nozzles spaced 9 inches apart in two parallel ½-inch pipes. These were placed 3.65 feet apart or directly over each side of the soil tank and 4 feet above the soil when the tank was level. A higher distance would have been preferable as the greater the distance the raindrops can be made to fall, the more nearly their impact approaches that produced by natural rain. In this experiment the height of the ceiling limited the height at which the sprinkler pipes could be set. It was necessary to have an additional 4 feet above the sprinkler pipes for the upward shot of the spray before the water fell. The nozzles in the pipe were set so that the sprays of water from one side were half way between those from the other side. The pipes were 15 feet long, extending 18 inches beyond each end of the soil tank. They were supported by a cross arm set a foot from each end of the pipes. A cut-off valve was placed in the sprinkler pipe directly above the back end of the soil tank.

During the first run, the oscillation and longitudinal movements were executed at the same time by one lever movement. A 45-degree spiral groove 10 inches long was cut in the sprinkler pipe between the end and the valve. A ⅜-inch pin extended from the support arm up through this spiral groove in the pipe. As the pipes were moved back and forth, they automatically oscillated. It was found that the distribution of the rain was not as good as when two independent movements were executed. The sections of pipe with spiral grooves were replaced by sections with straight grooves. A pin attached to the oscillating lever was put through these grooves. The sprinkler pipes were oscillated in the same direction by moving the lever arm at right angles to the direction of the pipes. It would have been desirable to have oscillated the pipes in opposite directions. By means of another lever, the pipes could be moved longitudinally back and forth a distance equal to the spacing of the nozzles (9 inches).

With the exception of the 4-inch application of rain, the water was applied through No. 60 gage standard nozzles (0.94 mm. inside diameter) placed 9 inches apart. The holes in the sprinkler pipes, into which the nozzles were screwed, were tapped as nearly straight as possible. The 4-inch application was obtained by using larger nozzles (No. 57 gage or 1.14 mm. inside diameter) under the same head as for the 3-inch application with the No. 60 gage nozzles. The latter nozzles had a stem extending out about an inch from the pipe. A nozzle with a stem is better suited to artificial rain application than the standard sprinkler nozzles as the direction of the spray can be adjusted by bending the nozzle by a light blow. Since it is very difficult to tap all the holes in the pipe exactly straight, the water can not be applied uniformly unless the nozzles can be adjusted after they are screwed into the pipe. The direction of the spray from the standard nozzle can not be adjusted.

Calibration. To determine the quantity of water which would be applied, a small venturi meter was inserted in the supply line between the overflow tank and the sprinkler pipe but was discarded before the erosion experiments were started. A discharge curve (Fig. 6) was drawn and used for determining the quantity of water

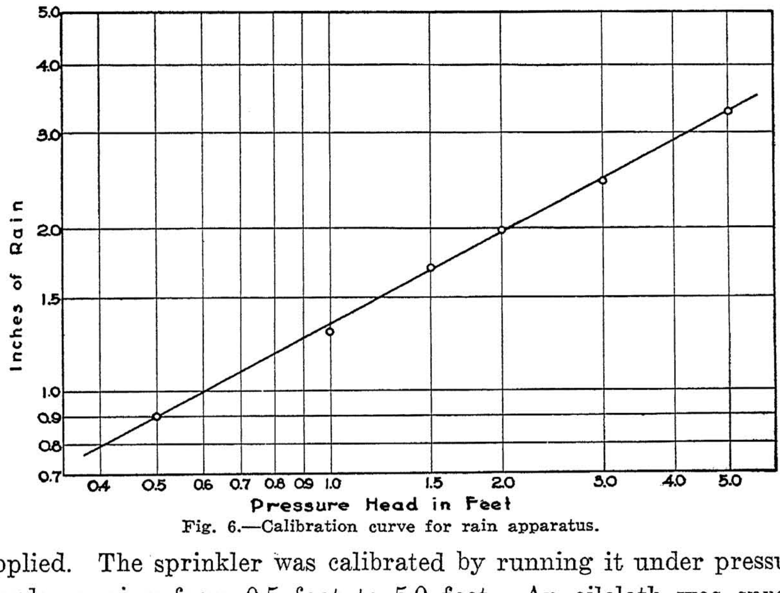

Fig. 6.—Calibration curve for rain apparatus.

applied. The sprinkler was calibrated by running it under pressure heads ranging from 0.5 foot to 5.0 feet. An oilcloth was spread over the soil to prevent any water from being absorbed. The quantity of water applied during each 10-minute interval for 30 minutes was weighed and converted to inches of rain.

Later when a rain of a given intensity was to be applied, the overflow tank was set at the proper pressure head to give this application. To insure greater accuracy the intensity was checked again by measurement before each run. If necessary, a slight adjustment in pressure head was made to give the desired intensity.

Application of rain. After the soil was ready and the soil tank set at the required slope, the rain was applied at a constant intensity for a period of 1 to 6 hours. (See Fig. 7.) The first three runs with

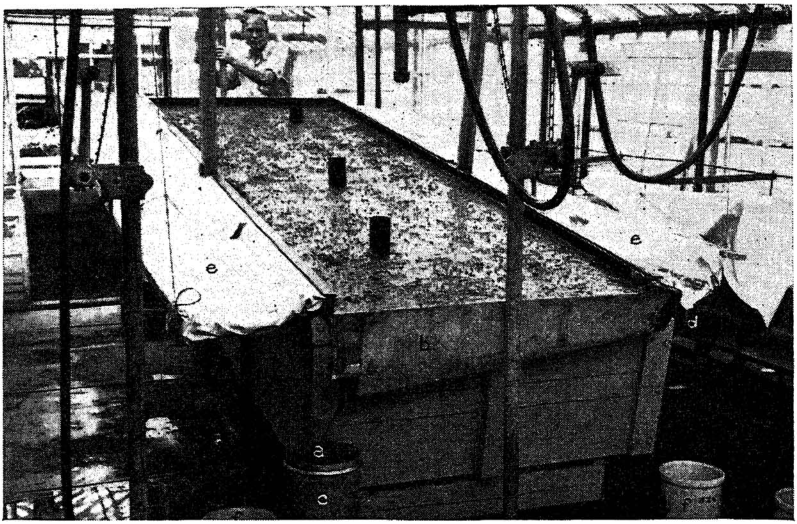

Fig. 7.—Applying a 3-inch rain on a 16 per cent slope: a, muddy runoff being discharged from trough (b) and caught in can (c). d, water thrown over soil tank running off end of apron (e) on which it was caught into jar (f).

rain intensities of 1.50, 2.00, and 3.00 inches per hour were applied on an 8 per cent slope for a period of 6 hours. These first runs were made by varying the rain intensity on a constant slope, but after that the procedure was changed to vary the slope with a constant rain intensity. Rain intensities of 0.90, 1.50, and 3.00 inches per hour were applied for a period of three hours on all slopes except the 8 per cent. Rain intensities of 2.00 and 4.00 inches per hour were applied for only one hour.

As the rain intensity was increased, the distance which the rain drops fell also increased. For a rain intensity of 0.90 inch per hour the spray was shot up into the air only 0.5 foot, for a 2.00-inch rain 1.5 feet, and for rain intensities of 3.00 and 4.00 inches per hour, the spray was shot up 3.5 feet. The total average fall of the rain drops ranged from 4.5 feet to 7.5 feet for rain intensities of 0.90 to 4.00 inches. Since the rain intensities of both 3.00 and 4.00 inches per hour were obtained by the same pressure head (but different size nozzles) the height of spray was about the same.

During the rain application the pipes were oscillated manually at an average rate of one complete oscillation every two to four seconds. For the lighter applications (up to $1\frac{1}{2}$ inch per hour) the pipes were oscillated through an arc of 45 degrees but less with heavier applications. In addition to the oscillations the pipes were moved longitudinally a distance of about one inch every 10 to 12 oscillations until a distance of 9 inches (nozzle spacing) had been reached, then the direction was reversed.

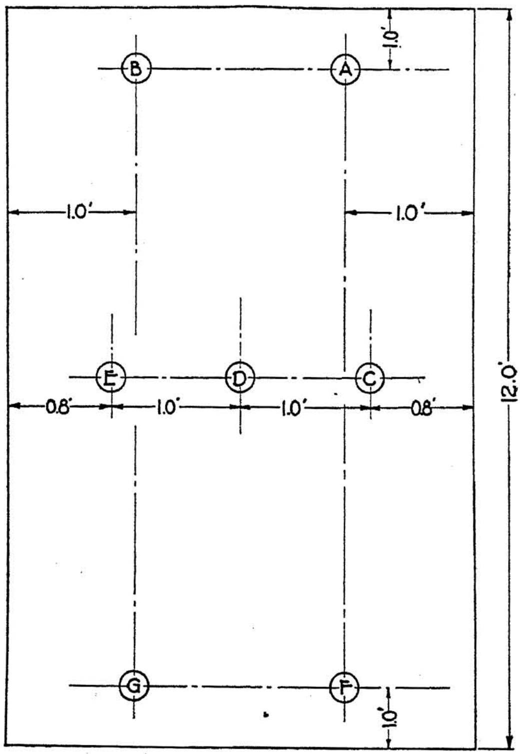

Fig. 8.—Location of rain gages on soil tank.

While oscillating the pipes, a small quantity of water was thrown outside the soil tank. This was caught on an oilcloth apron and carried to one end and discharged into a can. The overthrow or lost water was weighed every 20 minutes and the quantity subtracted from the total quantity sprinkled during that time.

Rain distribution. The greatest problem in using artificial rain is to get uniform distribution. The staff at the Soil Conservation Experiment Station, Bethany, Missouri, has done considerable work in perfecting an artificial rain apparatus that gives uniform distribution on an area of 1/100 acre or more. The writer received many helpful suggestions from them.

The longitudinal movement in addition to the oscillation gave fairly uniform distribution as indicated by the results given in Table 5, but even then the distribution was far from perfect.

TABLE 5.—RAIN DISTRIBUTION OVER SOIL TANK

Location		Rain intensity of 1.50	2.00	4.00
		Inches fell in 1 hour		
Upper end	A		2.06	
	B		2.00	
Center	C	1.44		3.85
	D	1.80	2.22	4.32
	E	1.44		3.85
Lower end	F		1.95	
	G		1.85	

Measurement of Infiltration

Before any erosion tests were made, the rate of infiltration was determined in triplicate by forcing iron cylinders, 0.218 foot inside diameter and one foot long, into the soil. (See Fig. 3.) The top of the cylinders were about two inches above the surface of the soil. Water was applied into the cylinder as fast as the soil would absorb it by means of a Florence flask with petcock. The quantity of water taken up by the soil was measured for each 5-minute period during the first 30 minutes, for each 10-minute period during the second 30 minutes, and for each 30-minute period during the next two hours. A similar test was made after the erosion experiments were completed.

The infiltration for each rain was determined by taking the difference between the rain applied and the inches of runoff. After 30 to 60 minutes, part of the infiltration water passed through the soil and was caught as percolation water. The percolation water was weighed every 10 to 20 minutes, depending upon the rate of infiltration.

Measurement of Runoff and Soil Losses

The runoff was caught in cans and weighed for each 10-minute period. After weighing, the contents in the can were thoroughly mixed and sampled to get the per cent of soil carried away by the runoff.

The sampler consisted of a 100 cc. Florence flask set in a sheet iron sheath attached to a wooden handle. The cork in the flask was attached to a wire extending up the handle. The sampler could be used to stir the suspension as well as to take a sample. After stirring vigorously, the cork was pulled out by means of the wire and the sampler lifted out at such a speed that the flask would be full just as it reached the top. This sample of approximately 100 cc. was immediately poured into a beaker and weighed. The gurgling of the water flowing out of the flask prevented the sediment from lodging on the sides. The water was evaporated and the dry soil weighed. The per cent of soil thus obtained multiplied by the total weight of runoff material, gave the soil loss for each 10-minute period.

The time was recorded when the rain started, when runoff occurred, when the rain stopped and when runoff ceased. The runoff occurring after the rain, was weighed in the same manner as that which occurred during the rain.

EXPERIMENTAL RESULTS

Infiltration

Rate of infiltration. The first infiltration test was made under drier conditions than when most of the erosion tests were made. Although the soil had two 2-inch applications of rains during the previous 10 days, the excess moisture had drained from the deeper soil and the surface had become dry. The moisture content of the upper 10 inches of soil was as follows:

Depth in.	Moisture content per cent	Degree of saturation per cent
0- 1	9.6	28.4
1- 3	24.0	71.1
3- 6	26.4	78.2
6-10	27.5	81.4

The rate of infiltration during the first test was 1.5 to 1.9 times that of the second test which was made following the soil erosion tests when the lower soil was practically saturated. (See Fig. 9.)

TABLE 6.—INFILTRATION TESTS IN SOIL TANK

Time minutes	Cylinder tests No. 1 inches	Cylinder tests No. 2 inches	Ratio No. 1 / No. 2	During rain 3″ rain 0 slope	During rain grand average	Ratio Cylinder 2 / average
10	1.643	0.978	1.68	0.449	0.308	3.18
20	2.150	1.195	1.80	.583	.403	2.96
30	2.350	1.433	1.64	.671	.450	3.18
40	2.495	1.537	1.62	.757	.508	3.02
50		1.674		.823	.557	3.00
60	2.795	1.811	1.54	.892	.603	3.00
90	3.070	1.925	1.59	1.134	.761	2.53
120	3.370	1.982	1.70	1.340	.850	2.33
150		2.028			.976	2.08
180	3.960	2.074	1.91		1.073	1.94

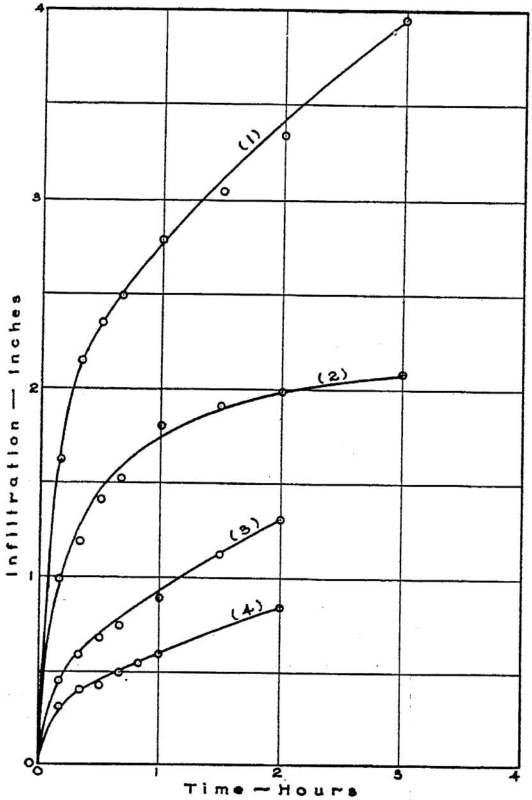

Fig. 9.—Total infiltration into soil in tank: (1) Before erosion tests were started and before the soil, below a depth of 10 inches, had reached capillary capacity. (2) After erosion tests were made and after the soil, below a depth of 10 inches, had reached a capillary capacity. (3) Infiltration during a 3-inch rain on a flat slope. (4) Average infiltration during all rains.

The moisture content at the time of the second infiltration test was as follows:

Depth in.	Moisture content per cent	Degree of saturation per cent
0- 1	12.6	36.7
1- 4	29.2	89.1
4-10	30.8	94.3

Under either condition, the rate of infiltration was much greater than the infiltration during a rain. In the cylinders the water was applied gently and it neither puddled the soil nor carried suspended material into the soil pores, while under rain conditions the surface soil was puddled and undoubtedly much suspended material was carried into the pore volume of the soil. The average infiltration during rains (rain minus runoff) was from one-third to one-half that obtained on similar soil conditions when applying the water

TABLE 7.—TOTAL INFILTRATION FOR DIFFERENT RAIN INTENSITIES

Slope	Soil Moisture content at		Time in minutes						
			10	20	30	40	50	60	120
Per	0-1 in.	1-4 in.	Infiltration						
cent	Per cent		in.	in.	in.	in.	in.	in.	in.
				4-inch rain					
2	11.8	22.0	0.289	0.346	0.375	0.406	0.432	0.454	
4	12.8	20.5	0.301	.366	.407	.429	.449	.464	
8	13.5	20.2	0.348	.424	.469	.499	.532	.562	
16	10.5	22.1	0.402	.533	.610	.672	.724	.784	
Av.	12.2	21.2	0.335	0.417	0.465	0.502	0.534	0.560	
				3-inch rain					
0	16.5	26.3	0.449	0.583	0.671	0.757	0.823	0.892	1.340
1	19.5	25.6	0.313	.380	.426	.485	.519	.563	.755
2	12.1	26.8	0.364	.475	.551	.627	.682	.727	.993
4	19.9	26.7	0.232	.260	.277	.293	.308	.323	.430
8	19.7	27.2	0.227	.288	.330	.371	.376	.404	.686
16	20.7	26.7	0.197	.276	.304	.346	.367	.412	.600
Av.	18.1	26.6	0.297	0.377	0.426	0.480	0.512	0.554	0.800
				2-inch rain					
2	11.5	28.4	0.314	0.468	0.533	0.588	0.634	0.675	
4	19.8	28.1	0.236	.289	.318	.342	.370	.398	
8	10.9	25.4	0.314	.456	.538	.600	.655	.698	
16	12.6	29.2	0.319	.466	.537	.589	.637	.694	
Av.	14.2	27.8	0.291	0.433	0.495	0.545	0.594	0.638	
				1.50-inch rain					
1	17.4	25.4	0.251	0.375	0.452	0.510	0.571	0.629	0.844
2	18.6	23.3	0.251	.383	.484	.545	.583	.625	.825
4	16.4	27.7	0.213	.367	.467	.510	.541	.563	.662
8	11.6	23.1	0.248	.454	.561	.624	.688	.751	1.048
12	13.4	26.4	0.251	.366	.430	.488	.529	.566	.828
16	13.6	20.6	0.250	.365	.442	.502	.556	.588	.818
Av.	15.1	24.4	0.244	0.385	0.473	0.530	0.578	0.620	0.838
				0.90-inch rain					
4	14.4	27.1	0.150	0.276	0.413	0.550	0.674	0.784	1.180
8	22.0	28.8	0.150	.278	.365	.418	.464	.503	.743
Av.	18.2	28.0	0.150	0.277	0.389	0.484	0.569	0.644	0.912
Grand Average	14.9	25.0	0.308	0.403	0.450	0.508	0.557	0.603	0.850

gently in a cylinder. (See Table 6.) The rate of infiltration was greatest during the first 10 minutes of a rain, but decreased rapidly during the next 20 minutes. After a period of one hour, the rate of infiltration was low and approximately constant. (See Tables 7 and 8.)

TABLE 8.—AVERAGE RATE OF INFILTRATION FOR 10-MINUTE PERIODS

Slope	Soil Moisture content at		Time in minutes						
	0-1 in.	1-4 in.	10	20	30	40	50	60	120
			Rate of infiltration per minute						
Per cent	Per cent		in.	in.	in.	in.	in.	in.	in.
			4-inch rain						
2	11.8	22.0	.0289	.0057	.0029	.0031	.0026	.0022	
4	12.8	20.5	.0301	.0065	.0041	.0022	.0020	.0015	
8	13.5	20.2	.0348	.0076	.0045	.0030	.0030	.0030	
16	10.5	22.1	.0402	.0131	.0077	.0062	.0052	.0058	
Av.	12.2	21.2	.0335	.0082	.0048	.0036	.0033	.0031	
			3-inch rain						
0	16.5	26.3	.0449	.0134	.0088	.0086	.0066	.0069	.0063
1	19.5	25.6	.0313	.0067	.0046	.0059	.0034	.0044	.0032
2	12.1	26.8	.0364	.0111	.0076	.0076	.0055	.0045	.0044
4	19.9	26.7	.0232	.0028	.0017	.0016	.0015	.0015	.0018
8	19.7	27.2	.0227	.0061	.0042	.0041	.0035	.0028	.0047
16	20.7	26.7	.0197	.0079	.0028	.0042	.0021	.0045	.0031
Av.	18.1	26.6	.0300	.0080	.0048	.0053	.0038	.0041	.0039
			2-inch rain						
2	11.5	28.4	.0314	.0154	.0065	.0055	.0046	.0041	
4	19.8	28.1	.0236	.0053	.0029	.0024	.0028	.0028	
8	10.9	25.4	.0314	.0142	.0082	.0062	.0055	.0043	
16	12.6	29.2	.0319	.0147	.0071	.0052	.0048	.0057	
Av.	14.2	27.8	.0296	.0124	.0062	.0048	.0044	.0042	
			1.50-inch rain						
1	17.4	25.4	.0251	.0124	.0077	.0058	.0061	.0058	.0036
2	18.6	23.3	.0251	.0132	.0101	.0061	.0038	.0042	.0033
4	16.4	27.7	.0213	.0154	.0100	.0043	.0031	.0022	.0018
8	11.6	23.1	.0248	.0206	.0107	.0063	.0064	.0063	.0050
12	13.4	26.4	.0251	.0115	.0064	.0058	.0041	.0037	.0044
16	13.6	20.6	.0250	.0115	.0077	.0060	.0054	.0032	.0038
Av.	15.1	24.4	.0244	.0141	.0086	.0057	.0048	.0042	.0037
			0.90-inch rain						
4	14.4	27.1	.0150	.0126	.0137	.0137	.0124	.0110	.0083
8	22.0	28.8	.0150	.0128	.0087	.0053	.0046	.0039	.0042
Av.	18.2	28.0	.0150	.0127	.0112	.0095	.0085	.0075	.0063

Musgrave (24) obtained results which were in substantial agreement by the two methods of measuring the infiltration. However, his results were obtained on Marshall silt loam which has a more stable structure than Putnam silt loam (4).

The total infiltration during rains varied approximately as the square root of the time, while the infiltration values reported by Musgrave (24) for Marshall silt loam varied approximately as the three-fourths power of the time.

Effect of the initial soil moisture content. The initial soil moisture content had a greater effect on the rate of infiltration during the first 20 minutes than any other factor. The rate of infiltration varied approximately inversely as the square root of the soil moisture content at the beginning of the rain. (See Fig. 10.) After a period

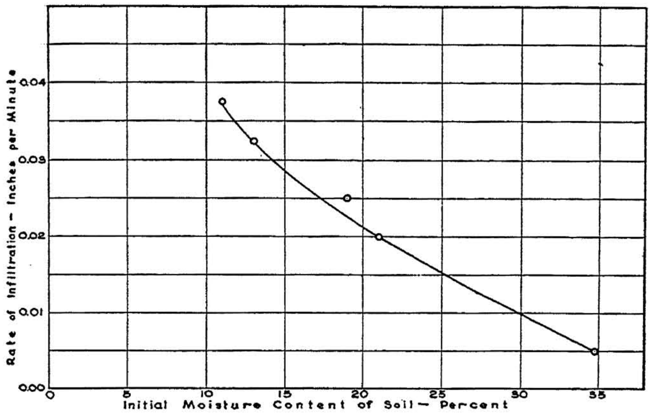

Fig. 10.—The effect of the initial soil moisture content on the rate of infiltration during first 10 minutes of rain.

of 30 minutes, the rate of infiltration became very slow, and after one hour, it was approximately uniform. Musgrave (24) also found that the infiltration was very small when the initial moisture content of the soil was high.

Effect of rain intensity. When the rain intensity was less than the rate of infiltration there was no runoff and the infiltration rate increased with an increase in rain intensity.

When the rain intensity was greater than the rate of infiltration, there was no appreciable difference in the rate of infiltration for different rainfall intensities, except for the 4-inch rain. However, it could not be determined whether the decrease in rate of infiltration for the 4-inch rain was affected by the rainfall intensity or by other factors. (See Tables 7 and 8.)

Effect of slope. The highest rate of infiltration during a rain occurred on a zero slope when 3.19 inches of rain per hour were applied. Inasmuch as there was a sheet of water ¼ to ½ inch deep over the soil surface, the falling rain drops dissipated their energy in the water rather than by dispersing the soil. Also having a sheet of water over the surface created a pressure head which induced a higher rate of infiltration. The next highest rate of infiltration occurred on a 16 per cent slope when 4.04 inches of rain per hour were applied. This case had the lowest initial soil moisture content.

For the 4-inch rains, the rate of infiltration happened to vary inversely as the slope. For other rains, there was no general trend with respect to the slope. As a whole, the data indicate that for slopes of 1 to 16 per cent inclusive, the rate of infiltration was not a function of the slope. (See Tables 7 and 8.)

Runoff and Soil Losses

Effect of slope. It is generally recognized that soil erosion increases as the slope of the land increases, but the relationship between slope and erosion losses has not been very definitely worked out. One of the objectives of these experiments was the determination of the effect of the degree of slope on runoff and soil erosion.

It was found that slopes above one per cent apparently had little or no effect on the per cent of runoff. After the surface soil was saturated, the runoff was 65 to 98 per cent of the rainfall, depending upon the intensity. For the 4-inch rains, the runoff happened to vary inversely as the slope, but for other rains there was no tendency to vary either directly or inversely with the slope. (See Table 9.)

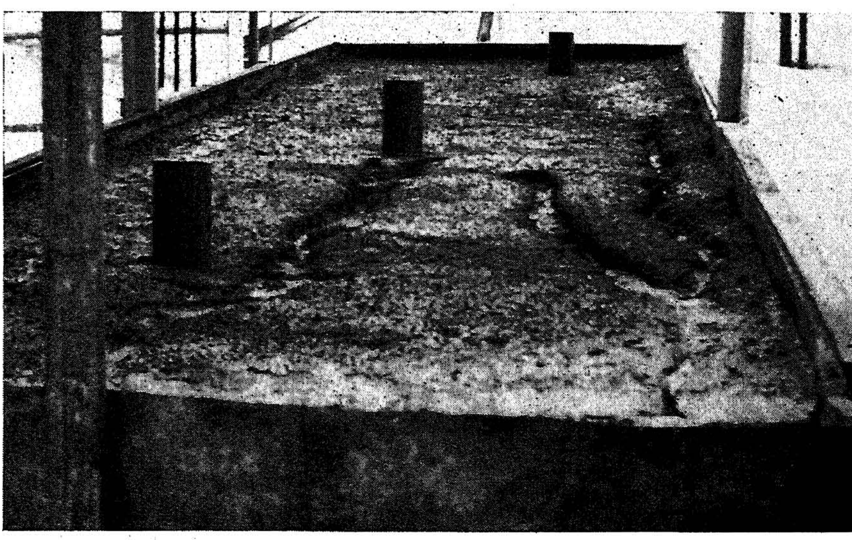

Fig. 11.—Effect of a rain of 4.03 inches in one hour on a 16 per cent slope.

TABLE 9.—WATER LOSSES FROM 1/1000 ACRE RESULTING FROM ARTIFICIAL RAIN ON FRESHLY CULTIVATED SOIL

Slope	Rain-fall	Soil moisture before rain		Time in minutes							
				10	20	30	40	50	60	120	180
per cent	in./hr.	0-1 in. per cent	1-4 in. per cent	Cumulative water losses in per cent							
2	4.16	11.8	21.8	53.0	72.7	81.4	84.1	86.4	89.0		
4	4.07	12.8	20.5	48.9	69.8	77.9	82.7	85.7	88.7		
8	4.07	13.5	20.2	45.2	67.3	75.6	80.5	83.5	86.1		
16	4.04	10.5	22.1	35.7	58.3	69.0	74.5	77.9	80.5		
0	3.19	16.5	26.3	0	36.8	53.1	61.0	66.4	70.8	79.1	
1	3.03	19.5	25.6	28.9	57.8	68.9	73.9	77.7	80.3	86.8	89.9
2	2.99	12.1	26.8	20.3	48.8	60.8	66.9	71.2	75.0	83.2	86.8
4	3.10	19.9	26.7	49.7	72.0	80.3	84.4	86.8	89.0	92.5	93.8
8	2.95	19.7	27.2	50.0	68.0	75.3	79.0	82.7	84.4	86.6	88.7
16	3.06	20.7	26.7	58.1	71.0	78.8	82.2	84.8	86.3	89.9	91.7
2	2.01	11.5	28.4	1.9	28.3	45.7	55.0	61.2	66.3		
4	2.06	19.8	28.1	25.0	55.2	67.7	74.3	77.6	80.4	88.6	91.7
8	2.02	10.9	25.4	3.6	30.3	45.3	54.5	60.2	65.3	84.0	
16	2.03	12.6	29.2	3.5	29.4	46.1	55.6	61.4	65.7		
1	1.48	17.4	25.4	0	20.9	36.8	46.6	52.1	56.5	71.0	
2	1.50	18.5	23.3	0	19.8	33.2	43.6	51.9	57.9	72.4	
4	1.51	16.4	27.7	4.2	20.9	33.3	45.8	54.1	60.3	76.8	82.5
8	1.47	11.6	23.1	0	5.5	21.3	33.9	42.3	48.4	64.3	
12	1.51	13.4	26.4	0	25.2	41.7	50.5	57.2	62.4	72.6	
16	1.47	13.6	20.6	0	25.2	39.8	48.8	54.7	60.6	72.6	
4	0.90	14.4	27.1	0	5.0	6.7	6.7	9.3	12.3	31.5	43.8
8	0.90	22.0	28.8	0	3.3	15.5	28.3	37.3	43.2	66.1	

For 3.00- and 4.00-inch rains, the amount of runoff required to remove one pound of soil was 4 times larger for a 2 per cent than for a 16 per cent slope, while for a 1.50-inch rain nearly 10 times as much runoff was required to remove a pound of soil from a 2 per cent as from a 16 per cent slope. Duley and Hays (14) obtained still higher ratios for a 1.00-inch rain.

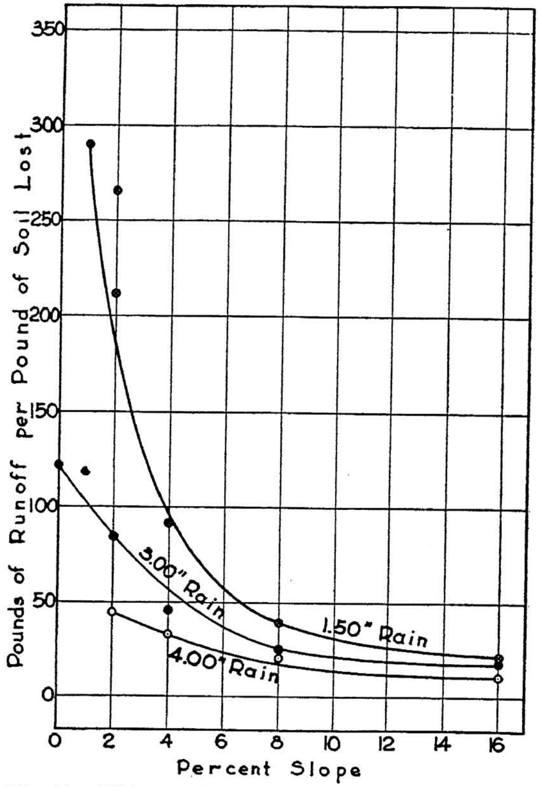

Fig. 12.—Effect of slope and rainfall intensity on relative density of runoff material.

These same relative conditions held from the second 10-minute period to the end of the rain.

On slopes of 4 per cent or less, no gullies were formed. The water ran off in a sheet over the surface. On 8 per cent slopes, a few small gullies occurred, especially for the heaviest rains. However, on 16 per cent slopes, gullying was very noticeable. Figure 11 shows the result of 4.03 inches of rain in one hour on a 16 per cent slope—a gully 4 inches deep with branches, extended nearly the full length of the soil tank. For 1.50- and 2.00-inch rains on the 16 per cent slope, the gullies were one to two inches deep and extended about half way up the length of the tank.

The relative density of the runoff material increased as the slope increased. (See Fig. 12.)

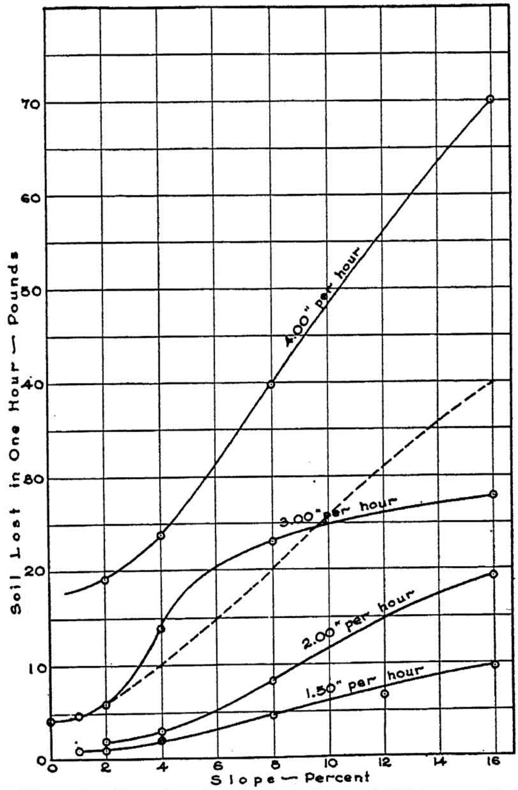

Fig. 13.—Pounds of soil lost from 1/1000 acre for different rainfall intensities on slopes ranging from 0 to 16 per cent.

The soil losses from the flatter slopes, 0-2 per cent, were not materially different for any given rain intensity. As the slope became steeper than 2 per cent, there was a substantial increase in soil loss. (See Table 10 and Fig. 13.) The soil losses resulting from the 3.00-inch rain did not follow the same trend as did the results from the other rains. The broken line, Fig. 13, shows the results which would have been obtained, had the trend followed the characteristics of the other rains.

All the curves are slightly S-shaped, but the one for the 3-inch rain is decidedly so. That is, the soil losses from slopes between 8

TABLE 10.—SOIL LOSSES FROM 1/1000 ACRE RESULTING FROM ARTIFICIAL RAIN ON FRESHLY CULTIVATED SOIL

Slope	Rain-fall	Soil moisture before rain		Time in minutes							
		0-1 in.	1-4 in.	10	20	30	40	50	60	120	180
				Cumulative soil losses							
per cent	in./hr.	per cent	per cent	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
2	4.16	11.8	21.8	2.61	6.08	9.40	13.08	16.38	18.72		
4	4.07	12.8	20.5	2.99	8.00	13.37	16.61	20.05	23.89		
8	4.07	13.5	20.2	7.65	17.10	24.48	29.78	35.06	39.45		
16	4.04	10.5	22.1	9.78	25.73	38.43	49.93	59.71	69.65		
0	3.19	16.5	26.3	0	0.73	1.60	2.45	3.31	4.20	8.24	
1	3.03	19.5	25.6	0.52	1.61	2.46	3.18	3.95	4.72	9.48	13.40
2	2.99	12.1	26.8	0.43	1.65	2.79	3.89	4.89	6.16	12.64	19.26
4	3.10	19.9	26.7	1.97	4.54	6.61	8.98	11.61	13.85	24.90	35.55
8	2.95	19.7	27.2	4.82	9.39	13.39	16.73	20.13	23.10	38.27	52.89
16	3.06	20.7	26.7	6.56	11.39	15.61	20.38	24.22	27.55	47.14	67.46
2	2.01	11.5	28.4	0.03	0.43	0.99	1.44	1.96	2.50		
4	2.06	19.8	28.1	0.30	0.94	1.51	2.04	2.55	4.04	7.71	12.11
8	2.02	10.9	25.4	0.20	1.09	2.42	4.28	6.11	8.33	14.20	
16	2.03	12.6	29.2	0.26	3.66	8.18	11.83	15.42	18.90		
1	1.48	17.4	25.4	0	0.18	0.40	0.61	0.77	0.94	1.91	
2	1.50	18.5	23.3	0	0.18	0.34	0.53	0.73	0.94	2.03	
4	1.51	16.4	27.7	0.06	0.26	0.61	1.11	1.59	2.19	5.00	7.93
8	1.47	11.6	23.1	0	0.12	0.79	2.07	3.33	4.37	10.84	
12	1.51	13.4	26.4	0	1.30	2.63	4.06	5.40	6.77	13.43	
16	1.47	13.6	20.6	0	2.30	4.09	5.79	7.41	9.28	18.14	
4	0.90	14.4	27.1	0	0.05	0.08	0.11	0.15	0.22	0.75	1.57
8	0.90	22.0	28.8	0	0.03	0.20	0.47	0.74	1.00	2.49	

and 16 per cent did not increase in the same proportion as the losses from slopes between 4 and 8 per cent. The S-shaped characteristic was more pronounced for the shorter duration, and less evident as the rain continued for a longer period of time. The soil losses from rains falling on a saturated soil usually showed an increasing rate of soil loss as the slope increased.

Similar results were obtained by Duley and Hays (14) and also by Nichols and Sexton (27). Diseker and Yoder (16) got results from a natural rain on a dry soil, which gave an S-shaped curve when erosion was plotted as a function of the slope.

Effect of rain intensity. The results of these tests showed that the effect of the rain intensity was by far the most important factor affecting runoff and soil erosion. Since the rate of infiltration was about the same for all rain intensities above 1.50-inch per hour,

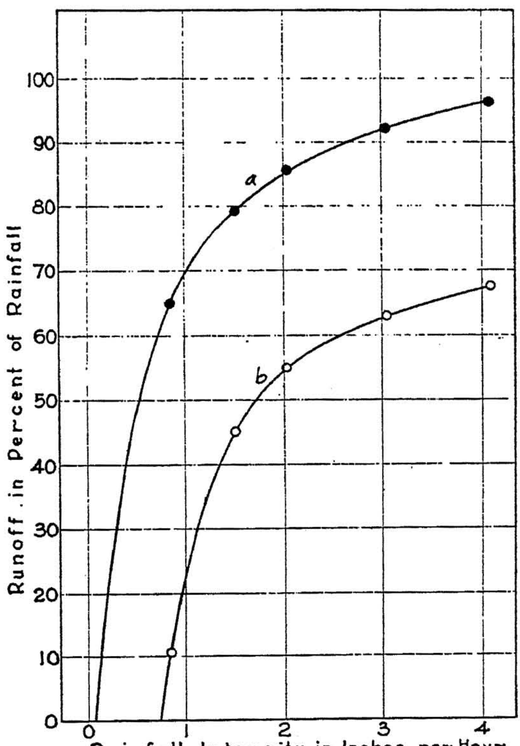

Fig. 14.—Effect of rainfall intensity on the per cent of runoff when one inch of rain fell on: (a) a saturated soil (b) a dry soil.

the total runoff increased as the intensity increased. (See Table 9 and Fig. 14.) The partial runoff for any 10-minute period increased as the rain continued, until 65 to 98 per cent of the rainfall was running off, depending upon the rainfall intensity. The highest intensity caused the highest percentage of runoff.

The rainfall intensity had a greater effect on the soil loss than on the runoff. After checking over the results, it was found that the soil erosion losses bore a geometric relationship to the rain intensity. To get this relationship, it was necessary to reduce the other variables to unity or to a constant. To eliminate the effect of the initial soil moisture content the quantities of soil lost were taken after the rain had been falling for 30 to 60 minutes. Since the 2.00- and 4.00-inch intensities were applied for only one hour, it was necessary to take

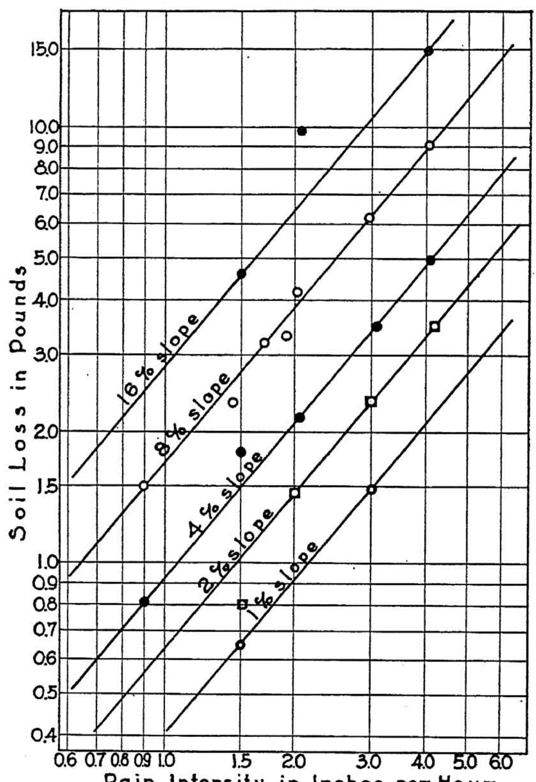

Fig. 15.—Pounds of soil lost from 1/1000 acre as a result of one inch of rainfall at various intensities.

the values from the second 30-minute period, while for the 1.50- and 3.00-inch rains, the values were taken from the second and third hour.

To get a comparison of the different rainfall intensities, the quantity of rainfall was taken as one inch (unity). The duration of the rain used in the tests was the time, in minutes, in which it took one inch of rain to fall.

Since the amount of soil lost had been determined for each 10-minute interval, it was possible to secure by interpolation the amount of erosion as a result of one inch of rain—falling at intensities ranging from 0.90 to 4.00 inches per hour. For a given rainfall intensity on a given slope, it was assumed that the erosion loss in pounds from a saturated soil varied directly as the duration of the rain in minutes. This assumption was very nearly correct for erosion losses resulting from rains which had continued for periods greater than one hour. However, the soil losses resulting from rains whose duration was *less* than one hour would not have come to equilibrium. The losses would be too large for rains of high intensity and too small for rains of low intensity. (See discussion on p. 43.)

The pounds of soil lost as a result of one inch of rain on a saturated soil are given in Table 11 and plotted as a function of the rainfall intensities in Figure 15.

TABLE 11.—SOIL LOSSES FROM 1/1000 ACRE RESULTING FROM 1.00 INCH OF ARTIFICIAL RAIN ON (a) FRESHLY CULTIVATED SOIL (b) SATURATED SOIL

Rainfall	Soil moisture—per cent: Before rain		Saturated		Duration of rain	Pounds of soil lost from: cultivated soil	saturated soil
	Inches						
in./hr.	0-1	1-4	0-1	1-4	Minutes		
			1 per cent slope				
3.03	19.5	25.5	33.9	32.2	19.8	1.65	1.48
1.48	17.4	25.3	33.5	33.0	40.6	0.63	0.62
			2 per cent slope				
4.16	11.8	22.0	32.8	30.2	14.4	4.27	3.50
2.99	12.1	26.8	33.9	32.2	20.0	1.75	2.36
2.01	11.5	28.4	38.8	35.2	29.8	1.00	1.44
1.50	18.6	23.3	33.5	33.0	40.0	0.54	0.80
			4 per cent slope				
4.07	12.8	20.5	32.6	31.7	14.8	5.58	5.00
3.10	19.9	26.7	32.6	33.5	19.4	4.46	3.51
2.06	19.8	28.1	34.3	32.8	29.2	1.50	2.16
1.51	16.4	27.7	34.3	32.8	40.0	1.14	1.80
0.90	14.4	27.1	34.3	32.8	66.7	0.21	0.81
			8 per cent slope				
4.07	13.5	20.2	31.2	29.4	14.8	12.33	9.12
2.95	19.7	27.2	34.3	32.8	20.4	9.62	6.10
2.02	10.9	25.4	38.9	38.1	29.6	2.42	4.25
1.92	24.1	27.4	34.3	32.8	31.2	1.50	3.30
1.70	20.7	26.4	34.3	32.8	35.2	1.27	3.20
1.44	15.0	23.0	34.3	32.8	41.6	1.76	2.33
0.90	22.0	28.8	34.3	32.8	66.7	1.16	1.50
			16 per cent slope				
4.04	10.5	22.1	31.6	30.2	14.8	17.67	15.00
3.06	20.7	26.7	34.3	32.8	19.6	11.27	6.53
2.03	12.6	29.2	40.2	36.9	29.6	8.14	9.80
1.47	13.6	20.6	35.3	31.9	40.0	5.79	4.92

For one inch of rain on any given slope, the rate of erosion varied as the 1.2 power of the rainfall intensity. The value 1.2 is the slope of the lines in the logarithmic graph.

That is, $E = K_1(I)^{1.2}$ (2)

where E = erosion from 1/1000 acres in pounds
K_1 = a constant for any given slope
I = rain intensity in inches per hour

Since K_1 is the value of E when $I = 1$, these values of K_1 for each slope can be plotted as a function of the per cent of slope. A graph (See Fig. 16) is thereby obtained which gives the erosion loss from

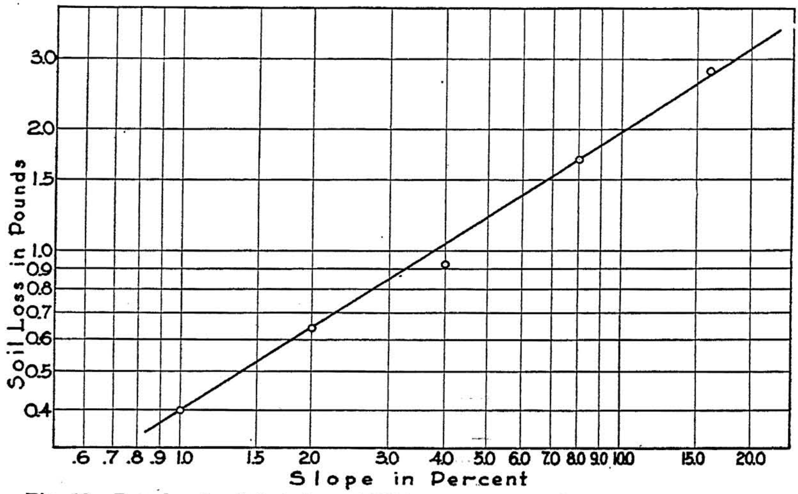

Fig. 16.—Pounds of soil lost from 1/1000 acre as a result of one inch of rainfall in one hour on various slopes.

different slopes for one inch of rain when the intensity is unity. From this graph the erosion loss was found to vary as the 0.7 power of the per cent of slope. For one inch of rain on any slope the erosion equation becomes

$$E = K_2(S)^{0.7}(I)^{1.2} \quad (3)$$

where K_2 = a constant = 0.4, which is the value of E when both S and I are unity
S = slope in per cent

If a different quantity of rain than one inch fell, then equation (3) must be multiplied by R (the amount of rain), but $R = IT$ or Intensity multiplied by Time in hours. Then for any quantity of rain, the erosion loss is

$$E = 0.4(S)^{0.7}T(I)^{2.2} \quad (4)$$

Since the area of the experimental soil tank was 1/1000 acre and there are 2000 pounds in a ton, the soil loss in tons per acre is obtained by multiplying equation (4) by 0.5 or

$$E_t = 0.2(S)^{0.7}T(I)^{2.2} \qquad (5)$$

Equation (5) gives the soil loss caused by a rain falling on a saturated soil. In case the soil is not saturated, several additional factors must be included in the equation. The most important of these are: (a) the duration of the rain, (b) the effect of the initial soil moisture content, and (c) the effect of the condition of the soil surface. Each of these factors are discussed under their respective headings. In regard to slope and soil loss, Diseker and Yoder (16) state as follows, "Soil losses are a function of slope under any given set of conditions. However, vegetation, surface shape and state of soil pulverization frequently exert a masking effect upon the slope factor."

Effect of duration of rain. To determine the effect of the duration of a rain at a constant intensity the first four runs were continued for a period of 6 hours. The following results were obtained. When a rain of uniform intensity was applied to a soil which was originally in a dry condition, there was no runoff during the first few minutes of the rain. As the rain intensity was increased, the time between the beginning of the rain and when runoff occurred decreased. (See Fig. 17.) After runoff started, there was a continual increase in the rate of runoff until the infiltration rate had become approximately constant. The increase in the rate of runoff was very slight between

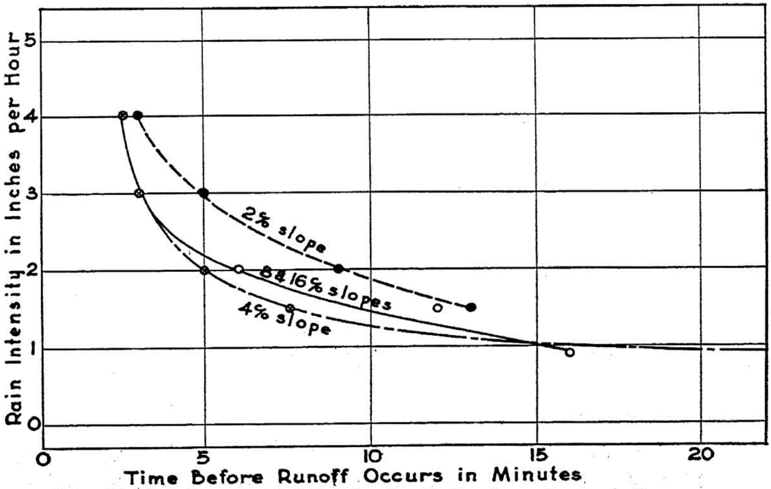

Fig. 17.—Relation of rainfall intensity to the time when runoff occurs.

one and two hours. (See Fig. 18.) After two hours the runoff and soil loss were approximately constant.

When runoff occurred during the first 10-minute period after the rain started, the maximum soil loss usually occurred during the second 10-minute period. By taking the soil loss during the second 10-minute period as unity, it was found that the average soil loss during the first period was 0.63; for periods after the second, the ratio decreased until only 0.70 as much soil was being lost during a 10-minute period between 1½ and 2 hours after the beginning of the rain as during the second 10-minute period. When runoff did not occur until the second 10-minute period, the maximum soil loss was likely to occur any time from the third to the sixth period except for the 0.90-inch rain when it occurred still later. During the second hour there was usually a decrease in the amount of soil lost. At the end of the second hour 0.80 as much soil was being lost as during the fourth 10-minute period.

The density of the runoff decreased during the first hour of the rain. When the rain continued longer, the density remained approximately uniform. (See Tables 12 and 13 and Fig. 18.) As a rule 1½ to 2 times as much runoff was required to remove a pound of soil at the end of one hour as at the beginning of the rain.

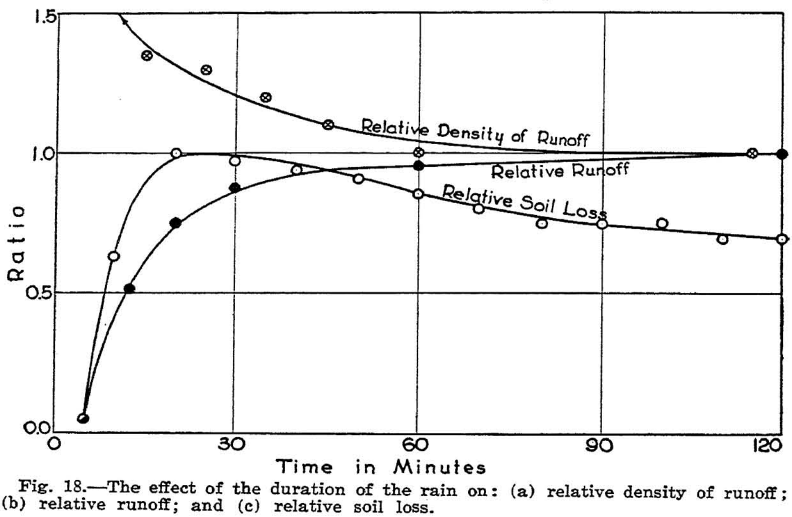

Fig. 18.—The effect of the duration of the rain on: (a) relative density of runoff; (b) relative runoff; and (c) relative soil loss.

Owing to the opposite trend in the per cent of runoff and the density of the runoff material, the rate of soil loss increased during the first 20 to 40 minutes then decreased during the next hour. After about 90 minutes, the soil loss was approximately constant. (See Fig. 18.)

Effect of the initial soil moisture content. Only one set of experiments was run to make a test on the effect of the initial soil moisture content, but in other cases where two or more runs were made, the results were compared. The results for a saturated soil condition were obtained by taking the second hour when the duration of the run was long enough. An initial moisture content of 12 to 14 per cent or about 40 per cent saturation seemed to give a maximum soil loss. (See Table 14.)

A large portion of the rain, especially at the beginning, was absorbed when the soil was in a very dry condition; consequently, there was little or no runoff. Although the first runoff which occurred had a high density, the small quantity resulted in a relatively low soil loss.

TABLE 12.—RELATIVE DENSITY OF RUNOFF

Time minutes	Rain 0.90	Rain 1.50	Rain 2.00	Rain 3.00	Rain 4.00
	Pounds of runoff per pound of soil lost				
	16 per cent slope				
10			10.4	10.1	5.5
20		12.5	12.5	19.6	7.7
30		21.9	13.6	26.2	11.0
40		25.3	17.6	22.5	12.6
50		27.4	18.1	29.2	13.6
60		27.2	19.2	33.1	14.7
Av. 10- 60		22.2	16.0	21.7	10.6
Av. 60-120		32.2		33.6	
	8 per cent slope				
10			14.4	11.7	9.2
20	82.2	61.4	48.7	21.5	15.0
30	84.2	39.6	43.2	25.5	18.5
40	81.4	44.4	33.9	30.7	27.6
50	85.4	40.0	34.7	32.5	28.3
60	97.2	35.4	46.2	36.4	35.0
Av. 10- 60	87.8	38.0	39.4	25.0	21.9
Av. 60-120	99.0	40.2		40.0	
	4 per cent slope				
10		49.2	64.7	29.5	24.4
20	70.0	100.0	102.8	42.9	27.6
30	75.0	92.6	125.3	55.5	26.8
40	75.0	90.4	136.8	48.2	45.7
50	150.0	100.0	140.3	43.4	44.9
60	180.0	87.7	137.5	52.6	42.8
Av. 10- 60	147.0	91.9	121.2	45.4	34.4
Av. 60-120	165.3	109.5	97.7	61.0	
	2 per cent slope				
10			57.7	53.7	32.7
20		127.0	105.2	72.0	42.2
30		217.0	110.2	85.0	45.2
40		222.0	140.0	87.9	40.5
50		236.5	125.2	99.7	45.3
60		256.5	141.2	87.7	69.1
Av. 10- 60		213.0	123.3	83.7	45.1
Av. 60-120		267.5		96.3	

TABLE 13.—RELATIVE DENSITY OF RUNOFF

Time minutes	0% slope	1% slope	
	Rain		
	3.00	1.50	3.00
	Pounds of runoff per pound of soil lost		
10			64.3
20	118.5	133.8	91.8
30	119.5	171.8	123.3
40	121.8	212.0	141.3
50	124.7	261.0	138.4
60	133.3	255.0	145.0
Av. 10- 60	123.7	203.0	118.0
Av. 60-120	157.0	289.0	134.2

TABLE 14.—THE EFFECT OF THE INITIAL MOISTURE CONTENT ON EROSION

Slope	Rain intensity	Soil moisture content before rain		Time in minutes				
		0-1 in.	1-4 in.	10	20	30	40	60
				Cumulative soil losses				
Per cent	Inches	Per cent		lbs.	lbs.	lbs.	lbs.	lbs.
8	2.03	6.8	7.6	0	0.15	0.52	1.11	2.84
8	2.02	11.0	25.4	0.29	1.18	2.51	4.37	8.33
8	1.92	24.1	27.4	0.17	0.49	1.36	2.53	4.83
8	1.92	34.3	32.8	0.88	1.68	2.42	3.20	4.67
16	1.49	13.6	20.6	0	2.30	4.09	5.79	9.28
16	1.49	14.1	24.0	0	1.60	3.83	6.26	10.11
16	1.49	17.1	26.3	0	1.58	2.92	4.21	6.74
16	1.51	33.7	32.8	1.18	2.20	3.15	4.28	6.38
8	1.46	11.6	23.1	0	0.12	0.79	2.07	4.57
8	1.44	15.0	23.1	0	0.59	1.16	1.64	2.80

As the soil moisture content increased, the per cent of runoff also increased but the density of the runoff did not decrease until a moisture point was reached where the soil would no longer slake upon wetting. When this point was reached the rate of erosion decreased. Above this moisture content, there was no appreciable variation in the rate of erosion for any given slope and rain intensity.

Effect of the condition of the soil surface. The condition of the surface of the soil at the beginning of the rain was an important factor in relation to runoff and soil loss. Two inches of rain were applied in one hour on an 8 per cent slope under the following conditions:

(a) normal surface
(b) very dry pulverized surface
(c) rough, dry surface spaded 4-5 inches deep
(d) dry, hard, baked surface

In the regular run the soil was prepared in the manner described on page 17. The very dry pulverized surface was prepared in a similar manner, except that it was worked and dried for a longer time before applying the rain. Also, the soil which was added was in an air-dried condition. The rough dry surface was prepared by spading to a depth of 4 to 5 inches after the surface was dry, and then al-

Fig. 19.—Condition of the soil surface when spaded 4 to 5 inches deep and left rough.

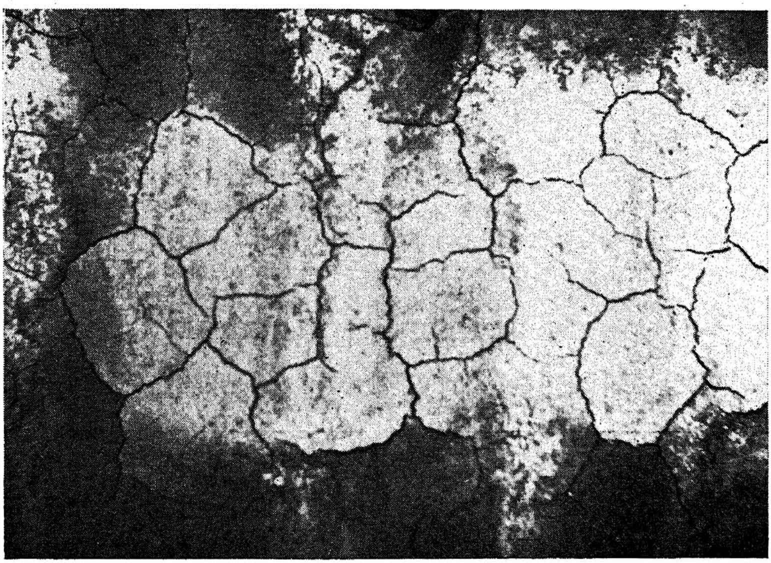

Fig. 20.—Condition of the soil surface when left to dry without cultivation. (Smooth, hard, baked surface).

lowed to dry again without further disturbance. (See Fig. 19.) The dry, hard, baked surface was dried without working. The soil had checked as shown in Fig. 20.

On the regularly prepared surface as described on Page 17, runoff occurred in 7 minutes after the rain started, while on the dry pulverized surface, runoff did not occur until after 12 minutes. The maximum runoff for a 10-minute period, which was the last 10 minutes in the hour, was only about three-fourths of the runoff during a corresponding period for the regular run. The density of the runoff from the regular run was higher than that from the dry pulverized surface. The average quantities of water required to remove one pound of soil for the runs were 39 and 70 pounds, respectively.

The runoff from the rough spaded surface did not start until 26 minutes after the beginning of the rain. During the first 30 minutes 0.99 inch of rain was absorbed or held by the depressions and 0.04 inch ran off, while during the second 30 minutes only 0.27 inch of rain was absorbed by the soil and 0.76 inch ran off. An average of 49 pounds of water was required to remove one pound of soil.

The runoff from the dry, hard, baked surface started 4 minutes after the beginning of the rain and carried a large amount of soil. Only 23 pounds of runoff were required to remove one pound of soil. Five-sixths of the rain which fell ran off, or twice the amount of runoff from either the dry pulverized or the rough, spaded surface.

The soil losses resulting from 2 inches of rain falling on a soil with different surface conditions are given in Table 15. There was not much difference in the amount of soil lost from the dry pulverized and the rough spaded surfaces. In each condition about three-fifths as much soil was lost as from the surface prepared in the normal way and one-half as much soil as from the dry, hard, baked surface.

DISCUSSION OF RESULTS

TABLE 15.—EFFECT OF THE CONDITION OF THE SOIL SURFACE ON RUNOFF AND SOIL LOSSES

	Time in minutes							
	10		20		30		60	
	Cumulative soil and water losses							
Surface treatment	Soil lbs.	Runoff per cent	Soil lbs.	Runoff per cent	Soil lbs.	Runoff per cent	Soil lbs.	Runoff per cent
Regular	0.20	3.6	1.09	30.3	2.42	45.3	7.61	65.3
Dry pulverized	0	0	0.12	9.1	0.48	20.9	2.84	42.6
Dry hard baked	1.86	41.2	5.50	63.2	8.71	72.7	16.68	83.6
Rough spaded	0	0	0	0	0.19	4.0	3.74	39.3

The results on runoff in relation to slope are partially substantiated by the results of other investigations. Ramser (28), in his analysis of runoff data from small agricultural areas, found that the slope of the land did not affect the runoff. The percentage of runoff resulting from both natural and artificial rains, presented by Diseker and Yoder (16), show no definite relationship to the slope for slopes of 5 to 20 per cent, inclusive, although the runoff was much lower for the zero slope. Their results from artificial rain on different slopes protected with a vegetative covering also showed no relationship to the percentage of slope. On the other hand, Duley and Hays (14) obtained a rapid and definite increase in runoff for slopes varying from 0 to 4 per cent but only a very gradual increase in runoff for those above 4 per cent.

The moisture content and the condition of the surface soil had a marked influence on both the amount of runoff and the soil loss. The effect of the initial soil moisture content on runoff and soil erosion as determined by these experiments did not agree with the results presented by Nichols and Sexton (27). They obtained a very large increase in both runoff and soil losses with an increase in the initial soil moisture content. In these experiments, although a continual increase was obtained in runoff until the soil was saturated, the soil losses became larger with an increase in the initial soil moisture content until the soil had a moisture content of about 40 per cent of its saturation capacity; then the soil losses decreased with a further increase in the soil moisture content.

The following theory is presented as an explanation of the above phenomena. When rain falls on a dry soil, the soil is slaked and thrown into suspension. If the rainfall intensity is high enough to cause runoff in a few minutes after the rain starts, this suspended material is carried off. Rain falling on a moist soil only packs it down and creates a pavement effect which sheds the water, but does not erode as severely as a soil originally in a dry state. In case a rain continues to fall on a soil that was originally dry, the suspended material is soon washed away and the remaining wet soil packs down into a smooth pavement-like surface. Although the runoff increases as the rain continues, the soil losses decrease. Results substantiating this theory were obtained in every case.

In the case of a rain of medium to light intensity falling on a very dry, absorptive soil, the soil absorbed the rain fast enough to prevent runoff until after the slaking had taken place and the soil was puddled. Two such cases were encountered in the foregoing experiments—one in which the surface soil was very dry and the other in which the soil was left dry and rough. (See effect of condition of the surface soil.) In both cases the relative density of the runoff material and the total soil lost were less than for the normal run in which the soil moisture content of the surface 4 inches was 2 to 4 times that of the very dry soil. In the case of the hard, smooth, dry surface, the runoff removed the suspended material before it had a chance to puddle. Consequently, a high soil loss occurred.

Although the aggregate analysis was not determined for the eroded material, it was evident that more large particles or aggregates than small ones were being washed off. When the container in which the runoff material was caught stood for 2 or 3 minutes, most of the suspended material settled to the bottom of the container.

Contrary to the general opinion, the rainfall intensity was found to have a much greater effect on soil loss than the degree of slope. Since the soil loss varied as the 2.2 power of the rainfall intensity and only as the 0.7 power of the slope, the rainfall intensity had 3 times the effect on erosion as the slope of the land. The rainfall intensities used in these experiments surpassed the maximum intensities for one hour expected to fall in Missouri once in 100 years.

Miller and Krusekopf (23) found that high runoff and excessive soil losses occurred during April, June, and September. The runoff and soil losses occurring in April were caused more from a high initial moisture content than from torrential rains, while in June and September, the losses were the result of torrential rains. Although rains of high intensity occurred during July and August, the runoff and subsequent erosion was not as severe as for June and September, since the total rainfall was much less and the evaporation and transpiration were greater.

If soil erosion is to be controlled, it is imperative that the surface of the soil is not left in a smooth condition during the season when rainfall of high intensities occur, since a soil in a bare, smooth, hard condition will erode considerably more than a similar soil in a rough condition. In case it is necessary to plow a field during the vulnerable period, the soil should be left in a rough condition.

The experiments of other investigators show that vegetation has a decided influence in retarding erosion. By keeping the soil covered with vegetation or in an absorptive condition, the erosive effect of high rainfall intensities and steep slopes can be reduced.

SUMMARY AND CONCLUSIONS

A Putnam silt loam surface soil from a timothy meadow was placed in a wooden soil tank 12 feet long, 3.63 feet wide (area = 1/1000 acre) and 2 feet deep. The set-up was in a greenhouse. Artificial rain was applied by an overhead sprinkling system.

The runoff and soil losses were determined at 10-minute intervals under cultivated conditions for (1) slopes ranging from 0 to 16 per cent, (2) rainfall intensities ranging from 0.90 to 4.00 inches per hour, (3) rain duration ranging up to 6 hours and (4) different initial moisture contents and surface conditions of the soil.

The infiltration was not affected by either the slope or the rainfall intensity, but varied inversely as the initial soil moisture content.

The percentage of slope had no apparent effect on the percentage of runoff for slopes above one per cent.

The percentage of runoff increased as the rain intensity increased but at a decreasing rate.

When the soil was dry before a rain, runoff did not occur until several minutes after the rain started. The time, elapsing between the beginning of the rain and the time when runoff occurred, decreased as both the slope and the rainfall intensity increased. After runoff started there was a continual increase in the rate until the infiltration rate had become approximately constant. This occurred from 1 to 2 hours after the beginning of the rain. After 1 to 2 hours the runoff was approximately constant.

The density of the runoff material decreased during the first hour of a rain. When the rain continued longer, the density remained approximately constant.

From 1½ to 2 times as much runoff was required to remove a pound of soil at the end of one hour as at the beginning of the rain.

The relative density of the runoff material increased as both the slope and the rainfall intensity increased.

The soil losses from a saturated soil increased as the 0.7 power of the slope, the 2.2 power of the rainfall intensity, and directly as the time of duration of the rain.

The amount of erosion from a soil which was in a dry condition at the beginning of the rain was affected by the initial soil moisture content and the condition of the soil surface, in addition to the degree of slope, the rainfall intensity and the duration of the rain.

The soil in a dry pulverized condition or one in a dry rough condition absorbed much more rainfall than when in a smooth, hard, baked condition.

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