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Slope Length of Claypan Soil Affects Runoff[1]

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Abstract. Measurements of runoff after prolonged irrigation of grass plots on a claypan soil (Mexico silt loam) showed that recession yields per unit area increased with slope length. Yields from slopes of lengths varying from 76 to 323 feet indicated return flow ('interflow') during runoff recession of at least 0.1 inch from the longer plots. During a simulated wet season using irrigation to supplement rainfall in the summer of 1965, per unit area yields were greatest for long plots, except for small events or events of long duration. The seasonal yield was 1.69 inches, or about 19% more from the long than from the short plots. Hydraulic conductivity measurements indicate that the predominant path of interflow is in the upper inch or two of the soil surface. However, soil moisture content and hydraulic pressure gradient changes during recession runoff indicated that there may be an interflow contribution from the loessal soil layer between weathered till and claypan. (Key words: Runoff; soil moisture; infiltration)

Runoff measurements from small watersheds or plots cannot always be used to obtain reliable estimates of water yields from large areas with similar soil and rainfall conditions. *Minshall and Jamison* [1962] found that the yield per unit area from sloping claypan soils in Illinois and Missouri may increase or decrease with slope length, depending on soil moisture conditions before the runoff-producing rains. They found that unit area runoff increased with slope length during prolonged wet periods, but that during soil moisture deficit periods unit area runoff for short slopes was equal to or greater than runoff from long slopes. They considered the increase in runoff with slope length for wet soil conditions to be the result of return flow from the soil to the surface.

In recent years, hydrologic investigations relating small watershed storm flow data to that from larger complex areas have been concerned with identifying reasons for the apparent gap between the sets of values. Ungaged interflow or quick return flow from the soil to the surface stream is thought to be the major factor explaining the differences. This study is one of those being made simultaneously at several research locations to identify this flow system.

The analytical model of *Klute et al.* [1965] has some application to the determination of interflow from the surface soil above a sloping claypan. They found that the flow pattern in the soil under uniform and continuous rainfall was dependent upon the slope length-depth ratio of the permeable soil layer. *Hewlett and Hibbert* [1963], from studies at the Coweeta Hydrologic Laboratory, concluded that contributions to base flow of streams may come from the unsaturated soil mass on the slopes and not necessarily from extended saturated underground aquifers. They consider the earth mantle of a steep watershed as a reservoir from which water may flow from unsaturated soil into

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saturated seep zones, from which it enters a stream as 'base flow.'

The quantity of outflow from an initially saturated porous column to a state of balance between gravitational and capillary forces will depend on the height of the column. The sloping silt loam surface layer above a claypan layer is essentially an inclined column. Assuming uniform depth of initially saturated soil above a claypan on a uniform slope, the quantity of drainage per unit area should increase with slope length. At saturation, the difference in hydraulic head between the top and the bottom of the slope is the difference in elevation. Therefore, the quantity of water stored from rainfall that will return to the surface as 'interflow,' as we choose to call it, should depend on slope length for any given slope. The experiment reported here was designed to test this hypothesis on runoff from plots 73 to 323 feet long on Mexico silt loam, a sloping claypan soil.

SOIL DESCRIPTION

A cross section of a typical Mexico silt loam in its slope-position relationship to Putnam and Gara silt loams is shown in Figure 1. The Mexico soil, because of large quantities of clay in the subsoil, has been described as claypan and classified as a Planosol [*Krusekopf and Scrivner,* 1962]. In the new system [*Soil Survey Staff,* 1960], it is called an Aeric Mollic albaqualf, fine, montmorillonitic, mesic. The Mexico soil developed in fine loess on a slope of about 3% in a landscape position below the nearly level Putnam series and above the steeper Gara, a soil developed from glacial till. The thickness of the loessal deposits varies from 18 inches at the Gara boundary to more than 5 feet at the top of the slopes.

The mechanical composition, moist bulk densities, and hydraulic conductivities of samples from a typical Mexico soil profile are shown in Table 1. All horizons are mostly silt and clay. Only the B_3 has more than 5% sand and the A_p and C horizons have more than 20% coarse silt. The clay content of the claypan (B_{21} and B_{22}) is about 50%, the minerals being dominantly montmorillonitic and of the expanding type [*Marshall and Whiteside,* 1944].

The hydraulic conductivity measurements were made with the double-tube equipment developed by *Bouwer* [1961]. Core samples taken both horizontally and vertically gave laboratory results in general agreement with the field values shown in Table 1. Core values found for the B_{21} horizon were 0.64 inch per day in the horizontal and 1.0 inch per day in the vertical direction. The very high value for the surface inch would be difficult to check with core samples. The double-tube field measurements are considered more reliable than measurements on core samples, since they are probably less affected by soil disturbance.

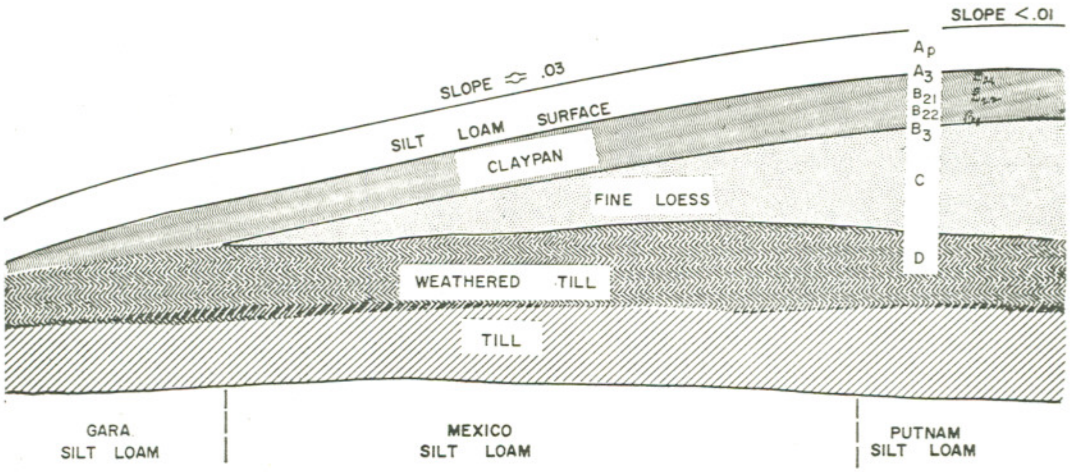

Fig. 1. Cross section of a typical Mexico silt loam soil in its slope-position relationship to Putnam and Gara silt loams.

TABLE 1. Mechanical Composition and Saturated Hydraulic Conductivity of Samples of Mexico Silt Loam from Experimental Site

Horizon	Depth, in	Moist Bulk Density,* grams/cc	Saturated Hydraulic K† in./day	Organic Matter, Per cent	Sand ($>50\mu$), Per cent	Coarse Silt (50–20μ), Per cent	Fine Silt (20–2μ), Per cent	Clay ($<2\mu$), Per cent
A	0–1	. . .	8130	. . .	. . .	. . .	. . .	. . .
A	1–2	. . .	470	. . .	. . .	. . .	. . .	. . .
A_p	0–7	1.50	. . .	2.3	1	41	46	12
A_3	7–11	1.30	. . .	1.9	2	20	50	28
B_{21}	11–16	1.03	1.0	1.7	4	9	37	50
B_{22}	16–25	1.22	0.1	1.7	4	13	35	48
B_3	25–34	1.48	. . .	0.9	18	10	36	36
C	34–50	1.62	0.2	0.7	5	22	44	29

* Bulk density at 0.33-bar suction.

† From field measurements with Bouwer double tube apparatus [*Bouwer*, 1961].

PROCEDURE

Since the sloping claypan soil, Mexico silt loam, is limited to slopes close to about 3%, comparison of the effect of elevation differences on this soil type can be made by varying plot lengths at the selected experimental site. A pasture area on Mexico silt loam at the Midwest claypan Experiment Farm was chosen for this study. The pasture species were dominantly bluegrass and orchard grass, with a thin stand of alfalfa.

The field layout of the runoff plots and the location of measurement devices are shown in Figure 2. The plot area was 323 feet long and divided lengthwise into 9 equal (12.5-foot-wide) plots with two 6-foot alleys between triplicate sets of plots. The upslope 240 feet of one outside set and the upslope 168 feet of the opposite outside set of three plots were covered with 6-mil black plastic. Triplicate sets of uncovered plots, 73 and 148 feet long, were isolated from the upslope plastic-covered plots by 12-inch-deep drainage ditches. Thus, the plot area was divided into triplicate sets of uncovered plots of 73, 148, and 323 feet long and of triplicate sets of covered plots 168 and 240 feet long. Ridges under the plastic diverted runoff from each plastic-covered plot to a flume. This gave a measurement of the quantity of water applied and surface runoff without return flow from the soil. The flumes at the end of all plots were equipped with stage recorders to give a continuous record during any time interval.

The lower terminal ends of all plots were located on Mexico silt loam about 50 feet upslope from the Mexico-Gara soil boundary (Figure 1). Each of the sets of plots was isolated from each other and the outside area by sheet aluminum barriers set in trenches 18 inches deep. The plots within groups of three were also isolated from each other by 6-mil black plastic sheeting set in trenches 12 inches deep. All joints in the barriers were sealed with black plastic cement. After the barriers were set, the trenches were backfilled with moist soil and tamped. A protective guard was used during tamping to avoid damage to the barriers. To prevent surface cross flow from one plot to another, earthen dikes were laid along and above each barrier. The flumes were calibrated for stage height versus flow, so that the stage recorder charts could be converted to runoff volumes and the total and recession runoff determined.

Pressures in the soil water were measured with quick-response recording tensiometers [*Klute and Peters*, 1962]. Four recording stations were established, one at the terminal end and the others at 80, 160, and 240 feet upslope along the plots. Tensiometers were installed in plots 3, 4, 5, and 7 opposite station 1 (Figure 2); in plots 3, 4, 6, and 7 opposite station 2; and in plots 4, 5, and 6 opposite stations 3 and 4. They were set at depths of 2, 10, 20, 30, and 46 cm opposite stations 1 and 2, and at additional depths of 61 and 91 cm opposite stations 3 and 4. Three of these were in the surface

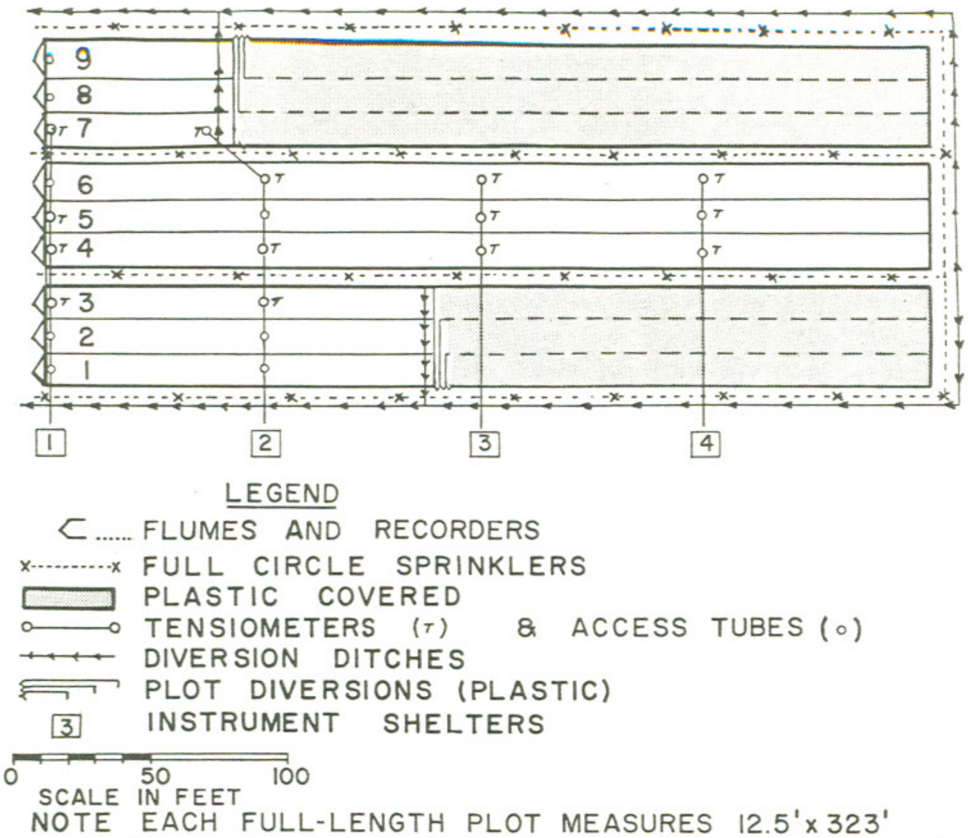

Fig. 2. Field layout of runoff plots showing locations of access tubes, tensiometers, sprinkler lines, ditches, and other features.

layers, one was at the A_3-B_{21} interface, two were in the B_{22} claypan layer, and one was in the loessal, silty clay below the claypan.

Access tubes for neutron moisture meter measurements were installed to a depth of 4 feet in all uncovered plots. These were located, one to each plot, in transect lines across the plots coincident with the tensiometer locations.

Readings for soil moisture at 15-cm (6-inch) depth intervals were made before and at the termination of each irrigation and at selected times during the recession-drying period of each test. Tensiometer readings were recorded at selected times for each test when the soil was moist enough to be within operation range of the porous cups used (no greater than about 1 bar of suction). Runoff records were kept for each test during irrigation and recession runoff. All soil depths are expressed in centimeters, to be conveniently comparable with the expression of soil water pressure in centimeters of water.

The grass was clipped at a height of about 2 inches a few days before each test, so that the plant height at the time of each water application was no more than 4 inches. Water was applied from full-circle sprinklers, to extend the wetted area more than 25 feet beyond the outside plot borders. This reduced the water pressure gradients between the soil inside and outside the border plots and minimized water loss through the claypan beneath the barriers to the soil around the plots.

The first test was made on June 25, 1964. Water was applied at about 0.5 inch per hour for 8 hours. This was followed on July 15 by another test of about the same rate and duration of application. There was some indication of piping along the back-filled barrier trenches. Late in July, while the soil was wet, the trenches were thoroughly puddled by a pneumatic tamper.

Another test was made August 18–19, 1964.

Water was applied at about 0.5 inch per hour for 20 hours. Variation of runoff from the plastic-covered plots indicated that differences due to sprinkler overlap, together with changes in wind velocity and direction, caused the average application on the plots to vary with time and location from the average rate by ± 0.05 inch per hour. These variations in rate of application were similar to those experienced during the other 1964 tests.

Several tests were made during the summer of 1965. The plots were kept wet by irrigations to simulate a high-rainfall season. Whenever rainfall was less than 1 inch for any 5-day period, water was applied to the plots by sprinkling at about 0.50 inch per hour. After the initial application of 2.50 inches on June 14, the amounts applied by irrigation varied between 0.85 and 2.50 inches. The heavier applications were made between July 25 and August

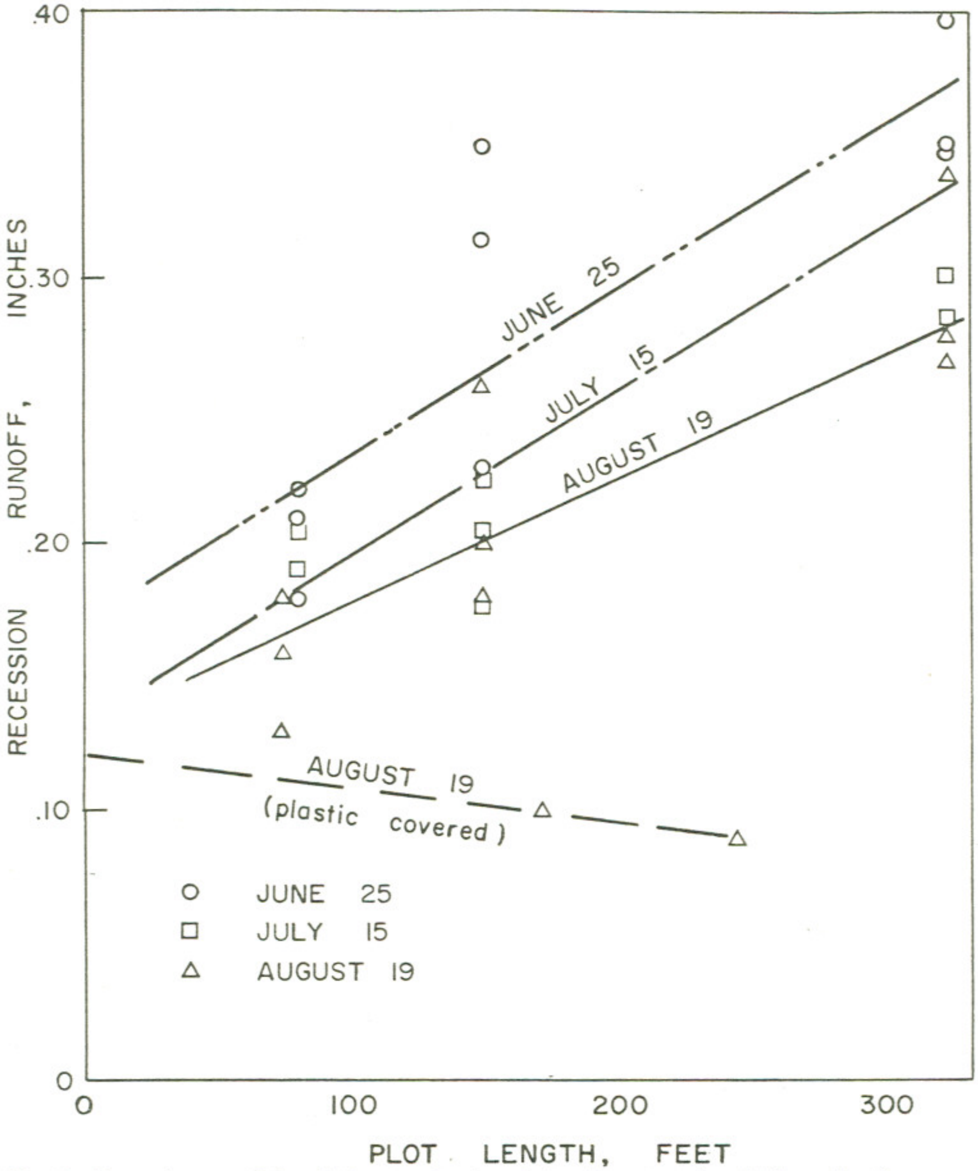

Fig. 3. Recession runoff in relation to plot length for three tests in which applications were prolonged so as to saturate the soil.

16, to compensate for the relatively high evapotranspiration losses associated with hot summer days. The recorders were kept in operation and the charts analyzed for total runoff for each rainfall or irrigation event.

RESULTS

Total runoff for three prolonged applications (June 25, July 15, and August 18–19, 1964) showed no consistent relationship to plot length, but recession runoff did (Figure 3). The total amounts for the August 18–19 test varied between 7.9 and 10.8 inches, whereas the recession runoff ranged from 0.13 to 0.34 inch and increased with plot length. Quantities for such long applications should reflect mostly the total amount applied, and plot differences should reflect accumulative variations in the application, such as those arising from changes in wind direction and velocity. Although the individual variation was seriously large for each test, the recession flow generally increased with plot length. Large variation in results for the same plot lengths for the June 25 test may be attributed in part to piping in some of the barrier trenches. This was reduced by tamping the barriers before the later tests.

Extrapolation of the August 19 curve of recession amounts versus length for the uncovered plots intersects the y axis at about 0.13 inch. The intersection is near that of the curve for the plastic-covered plots. The intercept value represents the water that would drain from the surface, exclusive of evaporative losses and interflow gains, after the application stopped or during the recession period. The slope of the plastic-covered plot curve is negative, since evaporative transmission losses during recession would increase with length. The slope of the curve for the uncovered plots is positive, because of the increase from interflow with increase in slope length. Assuming that evaporative losses are small enough to be neglected, the increases with plot length represent drainage outflow from the soil, or interflow, during the time of recession. Thus, the interflow contribution from the long plots was about 0.15 inch, or about 0.05 inch for each 100 feet of slope length.

Recession runoff amounts for the three tests and recession time for the plots on August 19, 1964, are shown in Table 2. Although the results are quite variable, both time of recession and runoff amounts generally increased with plot length.

TABLE 2. Recession Runoff from Individual Plots for Three Tests in 1964 and Time of Recession for the August 18–19, 1964, Test

Plot No.	Plot Length, feet	Recession Runoff, inches			Rec. Time, min.
		June 25	July 15	August 19	August 19
9	73	0.20	0.20	0.16	110
8	75	0.22	0.21	0.13	120
7	76	0.21	0.19	0.18	190
1	147	0.24	0.17	0.18	130
2	148	0.35	0.20	0.26	210
3	148	0.32	0.23	0.20	190
4	323	0.37	0.30	0.34	320
5	323	0.37	0.29	0.27	230
6	323	0.40	0.34	0.23	230

The runoff amounts from the plots for the series of tests in the summer of 1965 are shown in Table 3. For 10 out of 15 rainfall or irrigation events of more than 0.50 inch, runoff amounts increased with plot length. For 2 of these 15 events, there was no definite relationship between runoff and plot length. For 3 of the 15, the runoff decreased with plot length. For these three events, the accumulative duration of rainfall and/or irrigation was between 4.00 and 8.37 hours. For the four events of less than 0.50 inch, the runoff decreased with plot length. Thus, runoff increased with plot length for short-duration events of more than 0.50 inch but generally decreased with plot length for events of less than 0.50 inch or for larger events of prolonged duration. The total accumulative runoff amounts for the series of tests increased with plot length. The total runoff from the long plots was 1.69 inches, or 19%—more than from the short plots.

Changes in soil-water pressure and content. The tensiometer data from the July 13–15 test are presented to show soil-water pressure changes that occurred after irrigation stopped. Changes in soil water pressure at the 2-cm depth for a short plot and a long plot are shown in Figure 4. At the time irrigation stopped ($t = 0$), the pressure in the saturated soil was +2 cm of water at the 2-cm depth. With time ($t = 8$ hours, $t = 27$ hours), the short plot became a little drier and, hence, showed a

TABLE 3. Runoff from Interflow Plots, Summer of 1965

Date	Event	Rainfall or Irrigation Amount		Duration of Storm or Irrigation,* hours	Plot Length, feet		
		Previous 3-Day Period, inches	Day of Event, inches		75	148	323
					Runoff, inches		
June 14	Irrig.	0.00	2.50	5.00	0.55	0.89	1.43
29	Irrig. & Rain	0.01	0.90	2.50	0.47	0.51	0.72
30	Rain	0.90	0.70	2.45	0.29	0.36	0.51
July 6	Irrig.	0.00	0.85	1.70	0.07	0.11	0.14
8	Irrig.	0.85	1.00	2.00	0.28	0.44	0.43
9	Rain	1.00	0.72	2.00	0.39	0.37	0.44
26	Irrig.	0.00	2.20	4.40	0.70	0.80	0.91
30	Irrig.	0.09	2.25	4.50	0.84	0.96	1.05
Aug. 6	Irrig. & Rain	0.00	1.90	4.00	0.77	0.68	0.67
7	Rain	1.90	0.50	2.37	0.23	0.24	0.23
16	Irrig.	0.00	2.50	5.00	0.68	0.93	0.84
18	Rain	2.50	0.30	3.52	0.05	0.01	0.01
21	Rain	0.32	0.49	2.73	0.02	0.01	0.01
23	Rain	0.49	0.07	0.25	0.05	0.02	0.01
24	Rain	0.56	0.44	1.55	0.03	0.03	0.01
30	Rain	0.03	1.32	7.60	0.42	0.23	0.13
Sept. 3	Irrig.	0.00	1.34	2.60	0.31	0.93	0.58
4	Rain	1.34	1.94	6.67	1.51	1.72	1.33
15	Series of Rains	0.26	2.78	8.37	1.25	1.18	1.15
16	Total Runoff				8.91	10.42	10.60

* Total accumulated time of storm and/or irrigation during which measurable amounts of water as rain and/or irrigation was falling on the plots.

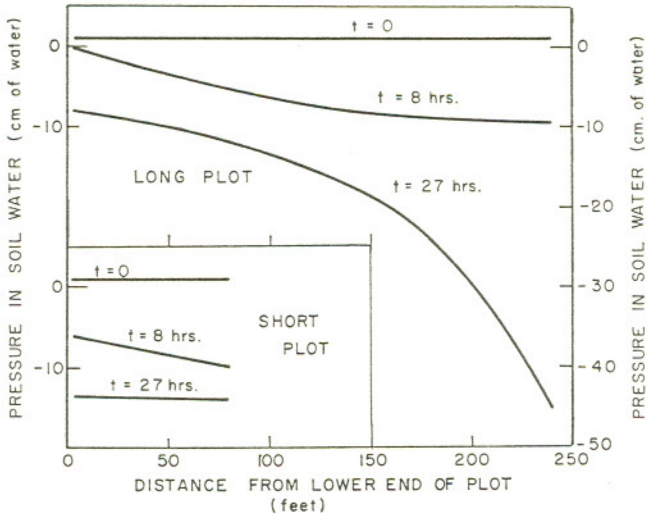

Fig. 4. Comparison of changes in soil-water pressure at the 2-cm depth for a long plot and a short plot at 0, 8, and 27 hours after irrigation stopped for the July 15, 1964, test.

greater negative pressure, than the corresponding positions on the long plots. Interflow drainage from the upper end of the long plot had contributed water to the lower end. After 27 hours, the upper end of the long plot had drained until the pressure reading was −45 cm, as compared with −8 cm for the lower end of the plot.

Soil-water pressure changes at different soil depths and times after the end of the August 18–19 irrigation for the 80-foot upslope location on a long plot are shown in Figure 5. The pressures were positive at all depths before irrigation stopped and during the first few hours of recession. In fact, the pressure below the claypan (46-cm depth) was high enough to indicate an upward gradient toward the soil surface. Thus, flow from beneath the claypan evidently contributed to the return flow from the surface layer. The quantitative amount of this contribution cannot be evaluated from hydraulic gradients alone. Hydraulic conductivity measurements in the flow direction are needed to estimate this contribution. The soil-water pressure responses at the different depths to a 0.5-inch rain during the drying period are noteworthy. There seemed to be little lag in the response of the deeper tensiometers behind those near the surface.

After all test runs, soil moisture measurements showed that the lower ends of the plots remained wetter than the upper ends for more than 300 hours after irrigation stopped. The changes in moisture content with recession and drying time for the lower end of a long plot, in comparison with those 240 feet upslope, are shown for three depths in Figure 6.

The moisture content response to the 0.5-inch rain is in agreement with the soil-water pressure increases in the soil below as well as above the claypan (Figures 5 and 6).

Estimates were made of the changes in soil moisture content that would accompany return flow in producing the increases in runoff. Assuming that interflow is mostly restricted to the surface soil, a 0.1-inch increase in recession

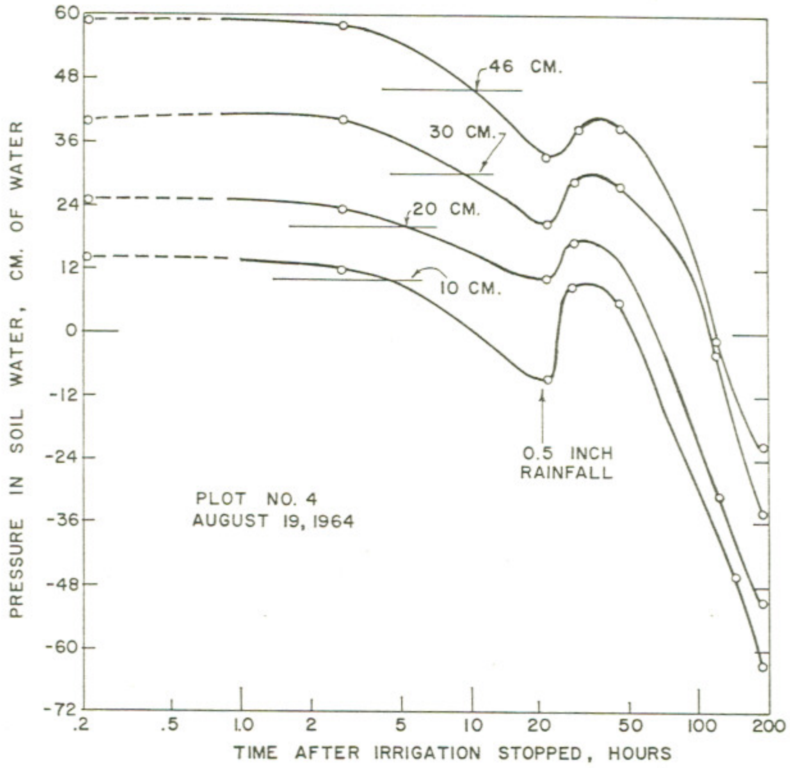

Fig. 5. Soil-water pressure changes with soil depth at the 80-foot up-slope location on a long plot with time after irrigation stopped during the August 18–19 test.

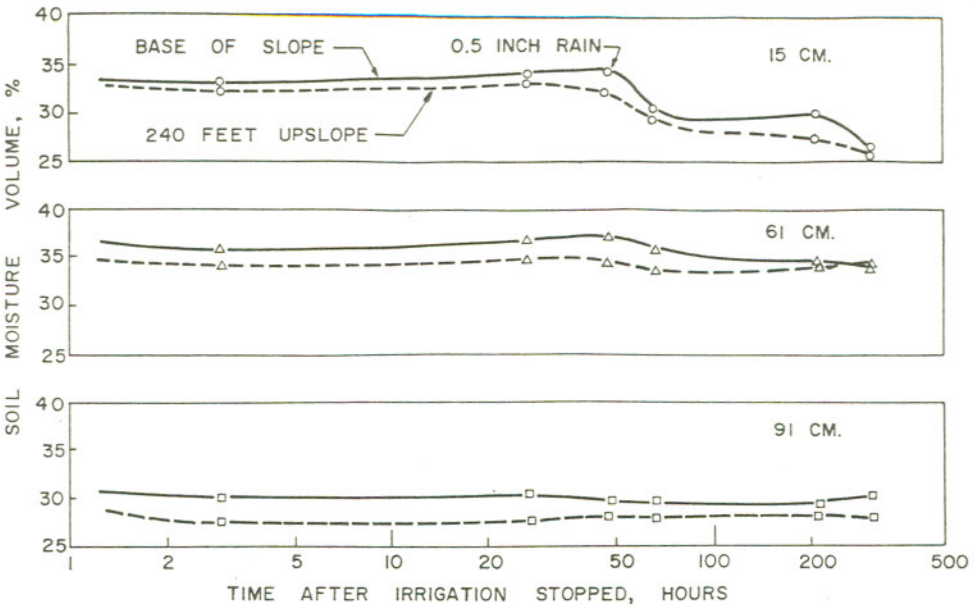

Fig. 6. Moisture content changes with time after irrigation stopped on August 19 at two locations on a long plot.

runoff from a long plot would result in an average change in moisture content of less than 1%. Since some of the contribution may return from beneath the claypan, the change would be even less than this estimate.

DISCUSSION

It is clear from the results of the tests reported here that recession flow from a claypan soil following long-duration storms or moderate storms on initially wet soil may be expected to increase with slope length. The increase appears to be due to return flow from the surface layer, the amount of which increases as the average hydraulic head increases with the height of the top of the slope above the bottom or outlet end. One day after irrigation, on July 16, 1964, the negative pressure (suction) in the soil water at the 2-cm depth was somewhat greater at the upper end of a long plot than at the upper end of a short plot. The increased suction with plot length was indicative of a greater contribution of return flow from the long plot than from the short plot.

Saturated hydraulic conductivity measurements indicate that the predominant path of interflow must be in the upper inch or two of the surface horizon (Table 1). However, it is evident from the soil water content and pressure measurements that interflow is not restricted to the surface (Figures 5 and 6).

At the end of the August 18–19, 1964, application of water, there was an upward flow gradient through claypan in the lower end of the plots. Initial pressures at the 10-, 20-, 30-, and 46-cm depths exceeded saturation pressures by 4, 5, 10, and 12 cm of water, respectively. The hydraulic conductivity of the loessal layer between the claypan and weathered till layers is a little higher than that of the B_{22} horizon of the claypan (Table 1). Since the loessal layer is 3 to 4 feet thick at the top of the slope under the plots, the principal restriction to flow would be the claypan. Some water could pass through the claypan at the upper end of the slope and return to the surface through the claypan at the lower end of the slope. Under saturated flow, the hydraulic pressure gradient in the lower one-half of a plot would be reversed against gravity toward the soil surface [*Klute et al.,* 1965]. If the effective hydraulic conductivity of the claypan is about 0.1 inch per day and the reversed gradient about equal to unity, 0.05 inch of interflow relative to the full plot length could pass through the deep subsoil and return to the soil surface in one day. As with flow through the surface layer above the claypan, return flow from beneath the claypan should increase with slope length, since hydraulic head in this layer would increase with elevation difference between the top and the bottom of the slope.

High evapotranspiration losses from the grass plots affected the quantity of return flow. All the test recessions of 1964 began in the early morning hours of hot summer days. Since evapotranspiration was about 0.3 inch per day, this would reduce runoff. Transmission losses due to evaporation from the water flowing on the surface and plant root extraction from the water in the soil would reduce both direct overland and subsurface flow. One would expect more interflow from a recession occurring during the cooler hours of the day or during the cooler seasons. *Minshall and Jamison* [1962] reported one cool season recession of 18-hour duration on the plot area of this experiment.

Transmission losses due to evaporation and deep percolation should increase with slope length. Thus, for long-duration storms and for storms of low precipitation, the total runoff per unit area decreased with plot length, whereas total yield for larger short-duration storms or irrigations increased with slope length. Since the plots were isolated from each other by barriers down to the claypan, cross-transfer of water from one plot to another would have to occur under the barriers through the claypan. Such transfers, if they took place, would be most likely from the upper end of the long plots to the shorter plots. The hydraulic gradient during runoff would not favor deep subsoil flow from the outer short- and medium-length groups of plots to the lower end of the three long plots situated in the central position (Figure 2).

In addition to transmission losses, there was probably some flow through the deep subsoil that bypassed the runoff gages at the end of the plots. Because of the greater hydraulic head, this loss would increase with plot length.

Thus, the increase in hydraulic head with plot length would increase recession interflow, whereas transmission losses by evaporation and deep percolation would increase with plot length. For a season of high rainfall on a claypan soil similar to the Mexico silt loam, recession interflow would be large, and per unit area amounts of runoff would increase with slope length. On the other hand, during a period of low intensity or long-duration rainfall, transmission losses would tend to increase and, hence, runoff would decrease with slope length. At McCredie, Missouri, during a year of about average rainfall, with respect to total amount and distribution, one may expect the effects of interflow and transmission losses almost to balance, so that the annual runoff yield would be about the same for short and long slopes on Mexico silt loam.

REFERENCES

Bouwer, Herman, A double tube method for measuring hydraulic conductivity in situ above a water table, *Soil Sci. Soc. Am. Proc., 25,* 234–339, 1961.

Hewlett, John D., and Alden R. Hibbert, Moisture and energy conditions within a sloping mass during drainage, *J. Geophys. Res., 68,* 1081–1087, 1963.

Klute, A., and D. B. Peters, A recording tensiometer with a short response time, *Soil Sci. Soc. Am. Proc., 26,* 87, 1962.

Klute, A., E. J. Scott, and F. D. Whisler, Steady state water flow in a saturated inclined soil slab, *Water Resources Res., 1*(2), 287–294, 1965.

Krusekopf, H. H., and C. L. Scrivner, Soil survey of Boone County, *Soil Surv. Ser. 1951, No. 12,* USDA and University of Missouri, 1962.

Marshall, C. E., and E. P. Whiteside, Mineralogical and chemical studies of the Putnam silt loam, *Mo. Agric. Exp. Sta. Res. Bull. 386,* 48 pp., 1944.

Minshall, N. E., and V. C. Jamison, Interflow in claypan soils, *J. Geophys. Res., 1*(3), 381–390, 1962.

Soil Survey Staff, Soil Conservation Service, USDA, *Soil Classification, A Comprehensive System, 7th Approximation,* U. S. Govt. Printing Office, Washington, D. C., 1960.

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revised January 10, 1967.)