station paper no. 132

october 1961

soil moisture as a source of base flow from steep mountain watersheds

by john d. hewlett

Southeastern Forest Experiment Station
Asheville, North Carolina

U.S. Department of Agriculture - Forest Service

Soil Moisture as a Source of Base Flow From Steep Mountain Watersheds

by

John D. Hewlett

Coweeta Hydrologic Laboratory

INTRODUCTION

This paper reports initial trials of an artificial soil profile constructed on sloping ground to test the theory that long slow drainage of soil moisture sustains base flow in mountain streams. Work is continuing which is expected to prove or disprove these preliminary results.

On heavily forested slopes such as those at the Coweeta Hydrologic Laboratory in western North Carolina, nearly all water in flowing streams has passed in some fashion through the soil mantle. Despite progress in studies of the hydrology of small watersheds, there remains a gap in our practical knowledge of the behavior of water during this passage. At Coweeta the movement and storage of soil water is being studied to determine its contribution to streamflow. The experimental area is characterized by deep friable soils and an 80-inch average annual rainfall which produces little or no overland flow during storm periods. Perennial streams flow from steep mountain slopes even during rare summer droughts of 6 weeks or more in duration. The average annual yield of water is 37 area inches, of which roughly 85 percent is base flow.

GROUND WATER AS A SOURCE OF BASE FLOW

Although the nature of the yield has long been studied by hydrograph analysis and water balance techniques, the immediate source of this continuous supply of water is not well understood. It has been accepted by most hydrologists that sloping ground-water bodies feed the streams during nonstorm periods by hydraulic gradients between the stream channels and the outer extremities of saturated aquifers (Hoover and Hursh, 1943). Calculations based on ground-water depletion curves and fluctuations in a ground-water well led Hursh and Fletcher (1942) to conclude that a saturated aquifer at least 2 acres in extent was required to provide the observed flow from a 7-acre watershed at Coweeta. The hypothesized ground-water area was not actually traced out, but was accepted as a reality on the basis of several well records in the vicinity.

During Coweeta's early years, a total of 28 wells from 5 to 35 feet deep were installed at various locations, and fluctuations in water levels were recorded from month to month. Although the wells showed depletion and accretion as expected, it was discovered after many years that, when pumped dry, most of the wells failed to recover until heavy rains occurred. The wells were charged apparently by excess water from heavy rains, and subsequent leakage provided the appearance of depletion. Twenty-one wells were abandoned with the conclusion that they had been reflecting, not ground-water levels, but simply variations in "cistern" storage. The remaining seven wells were located near stream channels or in narrow mountain flood plains, where recovery after pumping may have been aided by subsurface stream water. Although no thorough ground-water survey has yet been made, experience with these wells suggests that ground-water bodies may be restricted to relatively narrow zones along the stream channels.

Thus, neglecting evidence based mostly on calculations, no extensive ground-water aquifer has been demonstrated at Coweeta. In fact, taking into consideration the steepness of stream profiles and the precipitous valley slopes, it is difficult to picture a ground-water aquifer of sufficient extent to supply streamflow through the growing season, when most current rainfall is accounted for by expected rates of evapotranspiration. Indeed, to support the ground-water aquifer theory, on many of the watersheds, several covering a thousand-foot range in elevation, it would be necessary for ground water to exist for many weeks at hundreds of feet of hydraulic potential along stream channels which drop away at 45 percent slope.

Deep fissures in the underlying rock have been suggested as the location of extensive aquifers, although Coweeta watersheds apparently are underlain by watertight material. Fissures may supply some base flow. However, if a large percentage of flow came from this source, it would seem that the length of stream channels would shrink noticeably during the growing season and that many large springheads would be evident at lower elevations — a condition often characteristic of limestone areas. This does not seem to be the case at Coweeta, for the stream courses are remarkably stable and depletion tends to occur proportionally over the entire length during dry spells. Under present evidence, it seems unlikely that deep fissures are the origin of large percentages of base flow at Coweeta.

The soil mantle over much of the basin lies on slowly decomposing mica schists and gneisses. The depth of the weathered soil varies from 2 to more than 25 feet, and the mantle over many small watersheds averages about 6 feet in depth. After heavy rainfall, a 6-foot profile of medium-textured soil can hold briefly up to 30 area inches of water (42 percent by volume). Such storage potential, of which perhaps 8 inches (10 percent by volume) may be available for streamflow, dwarfs the apparent ground-water storage potential for these steep catchments. Where overland flow is negligible, nearly all evapotranspiration, ground water, and streamflow are derived from this huge temporary reservoir. If large ground-water areas cannot be demonstrated, it follows that unsaturated soil, or moisture in the field capacity range, must serve as the main storage aquifer and source of base flow on steep slopes. Almost imperceptible rates of drainage, operating over long periods of time on huge volumes of soil, may be sufficient in some cases to explain sustained base flow in mountain streams without recourse to the concept of extensive water tables or deep fissures in underlying rock.

REVIEW OF UNSATURATED FLOW IN FIELD SOILS

The literature on moisture movement in soil appears to be chiefly concerned with the application of Darcy's law, derived originally for flow in a saturated medium, to unsaturated flow. However, knowledge derived from these intensive studies has not been applied profitably to problems in hydrology. Concentration on agricultural drainage problems and the downward entry of irrigation water has tended to deflect attention from the mechanics of deep drainage subsequent to saturating rainfall. The subject is often closed with the statement that downward flow materially ceases after 2 or 3 days.

Nevertheless, the literature contains much indirect evidence to support the concept of unsaturated soil as a source of base flow in streams. Among the most pertinent early papers is one by Edlefsen and Bodman (1941), in which they described measurable drainage of a plot of soil after soaking by irrigation to a depth of 22 feet. With evaporation prevented by a multiple seal at the surface, they followed moisture changes in the top 9 feet over a period of 832 days. Drainage appeared continuous over the entire period (except for certain seasonal aberrations), and the average rate of downward movement between the 590th and 832nd day was calculated as 0.007 inch per day.

Ogata and Richards (1957) measured water content changes in the top foot of a sandy loam soil during a period of 50 days, and found downward flow after irrigation to be closely related to time by equations of the form

$$W = aT^{-b} \qquad (1)$$

where W represents moisture content in percent by volume, T is the time since beginning of drainage, and the values a and b are related to soil depth and physical properties. No time limit is indicated for the operation of this equation, suggesting an indefinite period of drainage. Robins, Pruitt, and Gardner (1954) measured a downward movement of 0.6 inch of water from the 0- to 3-foot layer during the 2nd to 8th day after irrigation. A simple calculation shows that this amount of moisture may eventually contribute 2000 cubic feet of water per acre to streamflow.

A recent paper by Nielsen, Kirkham, and van Wijk (1959) showed that drainage from a 5-foot profile of silt loam soil yielded from 0.5 to 1.2 inches of water between the 4th and 14th day after irrigation, or roughly 2000 to 3000 ft.^{3}/acre. Still more recently, Nixon and Lawless (1960) calculated from moisture measurements the movement of soil-water downward from a 20-foot profile of sandy soil. Approximately 11.2 inches of previously stored soil moisture passed downward during a 6-month dry season, from which they conclude that slow drainage from unsaturated soil may contribute significantly to ground-water recharge. These and other papers contain evidence that soil profiles exhibit gradients in moisture content for an indefinite period after the beginning of drainage, and indicate that, if the soil volume is large enough and no air-water interface impedes drainage, equilibrium in downward movement is attained only after a very long time.

Meinzer (1942) has called the region of the soil profile that is above the water table but below the effective rooting depth of vegetation, the "no man's land of hydrology." Remson, Randolph, and Barksdale (1960) concluded from their studies of this intermediate zone at Seabrook, New Jersey, that downward gradients of hydraulic head produce slow but continuous rates of drainage even during the season of evapotranspiration.

To this author's knowledge, no effort has been made to apply the increasing information in this field to the general problem of water storage and yield on steep slopes. The following experiment was designed to test the existence of soil moisture gradients in sloping profiles and to point out their importance in small watershed hydrology.

METHODS OF STUDY

Consideration of the difficulties in separating soil texture and depth effects from topographic and gravitational influences on natural slopes led to the adoption of a soil model for an initial study of the storage and movement of moisture on slopes. Techniques were developed as the experiment progressed; the first two phases of the study are reported here.

Phase I. The model used in Phase I was constructed of wood and concrete on a 40 percent slope under a forest canopy; pertinent details are diagrammed in figure 1. The artificial profile was 18 inches deep, measured perpendicular to the slope, 24 inches wide, and 24 feet long. The sandy loam soil excavated from the subsoil of a natural profile was mixed and carefully tamped into the structure to reproduce as closely as possible its original bulk density. Although quite free of stones, the soil was screened through a quarter-inch mesh to remove large aggregates which may have contained concentrations of colloidal material. Physical characteristics, as sampled from the model, are listed in table 1. The soil was analyzed by pressure plate (Richards and Weaver,

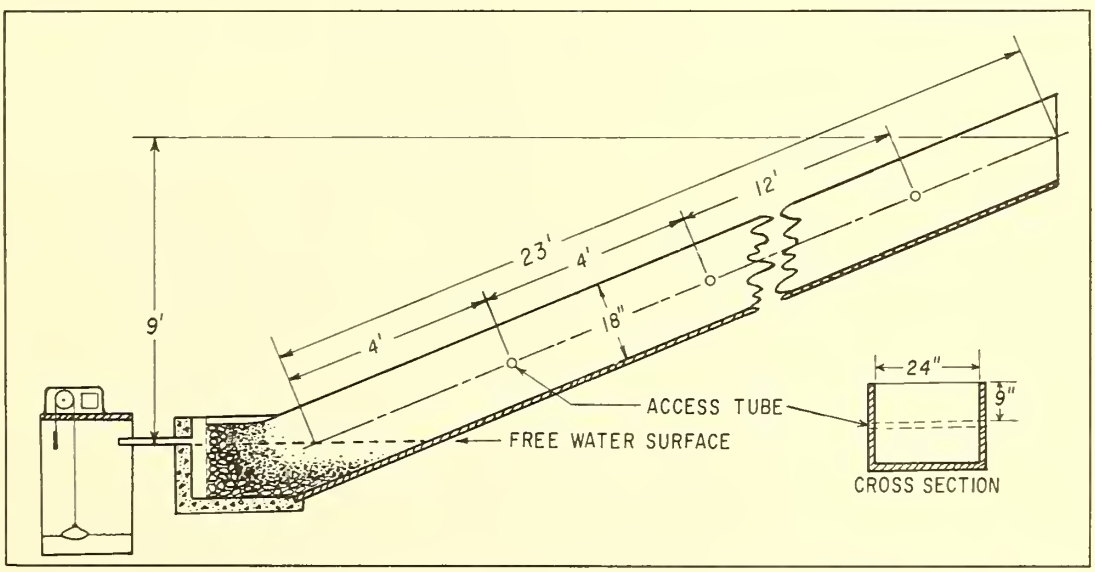

Figure 1. --Schematic diagram of the soil model as used in Phase I. The axis of the model rises at a 40-percent slope.

Table 1.—Physical characteristics of the soil used in the model, Phase I

Soil characteristic	Mean	Std. Dev.
Bulk density in original position	1.33	0.06
Bulk density when packed in model	1.35	.07
Percent moisture by weight when packed	18.0	1.0
Percent moisture by volume when packed	23.0	2.1
Percent moisture by volume at saturation	49.0	1.5
Percent moisture by volume under 40 cm. tension	36.0	1.3
Percent moisture by volume under 60 cm. tension	32.0	1.6
Percent sand*	60	—
Percent silt*	18	—
Percent clay*	22	—

*Measured by the Bouyoucos method of hydrometer analysis.

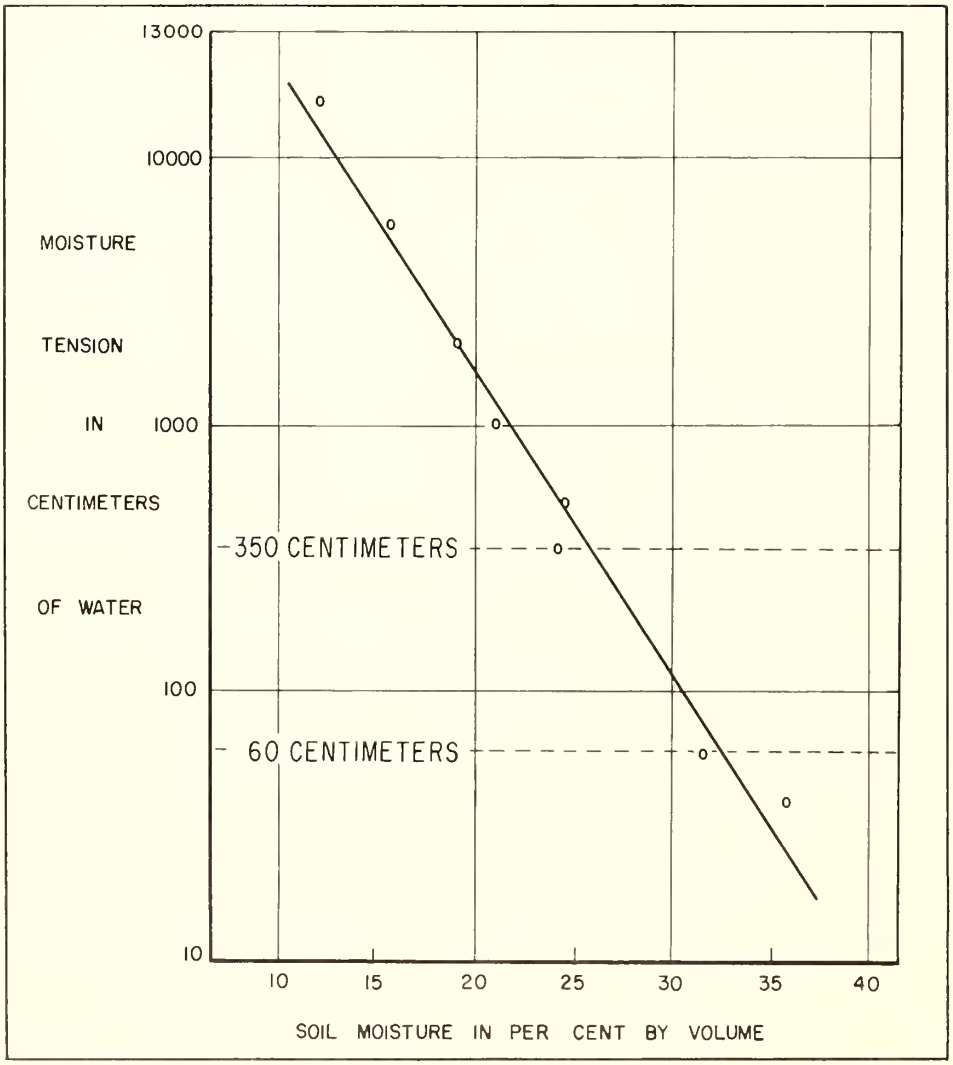

Figure 2. --Graph showing the relationship between soil moisture tension and soil moisture content. Each plotted point represents five or more samples of the experimental soil.

1943) and by tension table methods (Hoover, Olson, and Metz, 1954) to determine moisture retention characteristics from 40 to 15,000 cm. of water tension. Figure 2 shows a linear relationship over the specified range between moisture content and the logarithm of moisture tension.

A free water surface, or "water table," was maintained at a fixed level within the soil by an outlet pipe at the base (fig. 1). The difference in elevation between the "water table" and the top of the model was 9 feet. Special care was used in constructing the soil-water interface at the base of the sloping column. Downward-moving water passed from saturated soil (below the free water surface) into a sand-soil mixture, into coarser sand, fine gravel, and finally into larger spaces between 2-inch stone. In this manner, it was assumed that a gravelly stream bed was fairly well simulated.

The inside surfaces of the structure were lined with roofing paper, painted with tar, and sprinkled with sand to provide a good frictional surface. The surface inch of the soil column was mixed with ½ inch of organic litter and covered with a layer of cheesecloth to prevent puddling and erosion of the soil under sprinkling. After sprinkling, evaporation was practically eliminated by placing a double layer of polyethylene plastic over the surface.

Access tubes for the measurement of soil moisture by the neutron-scattering method were installed at 4, 8, 12, 16, and 20 feet (slope distance) from the water table (fig. 1). These were oriented horizontally to avoid the possibility of vertical movement of soil water along the tubes. The meter used was Nuclear-Chicago's Model 2800 scaler and P 19 probe, which provided estimates of moisture with a standard error of the order of 0.3 percent by volume. Readings were taken from the center of the column of soil, allowing ample margin to include the "sphere of influence" of the radioactive source at the moisture contents investigated. Repeated readings in the access tubes provided an exceptionally high degree of precision in estimating moisture changes with time.

Operating procedure was to soak the entire column by application of spray to the sloping surface. This was done repeatedly over a period of 48 hours to insure positive drainage and complete soaking. The ground water remained clear throughout this treatment. Moisture contents were measured at the five access tubes until it was determined that the entire column of tamped soil would not take more than 41 percent by volume (about 7 percent short of saturation) without exceeding the percolation capacity and causing surface runoff. The aim was not to simulate actual rain but rather a soil profile fully charged under sustained rainfall.

Within a few minutes after the last application of water, moisture was read at each access tube to establish beginning storage patterns. Repeated readings at the same points allowed moisture changes to be followed over the next 10 days.

The base of the model developed a leak during the soaking period, making it impossible, as was originally intended, to follow outflow accurately by a water-level recorder. However, it was observed that outflow continued throughout the 10 days and was still dripping from the bottom of the model when this phase of the experiment was terminated. Finally, comparison was made between soil moisture content and moisture under 60-cm. tension as determined in the laboratory on 18 undisturbed samples collected from three depths at six intervals up the slope of the model.

Phase II. In a renewed effort to obtain long-term records of outflow from the model, the water-table section was rebuilt by extending the concrete portion at the base, thus enclosing the entire water-table zone in concrete, and incidentally lengthening the model from 24 to 32 feet (fig. 3). Soil from the same source was repacked in the model, but a lower bulk density (average 1.24) resulted owing to inadequate tamping. A recording soil thermometer was located in the center of the column of soil, halfway up the slope. The soil was soaked and the entire procedure of Phase I was repeated, except that soil moisture and outflow were measured for 71 days, from August 11 until October 19. An FW 1 Friez water-level recorder gave a continuous record of water flowing out of the soil.

RESULTS

Phase I. During the soaking operation, small leaks developed along the column, particularly around the neutron probe access tubes, indicating positive hydraulic pressures within the soil. Within a short time after soaking, the leaks stopped, suggesting the development of negative pressures as tension was established on the column. Small holes bored in the soil at the base of the model revealed only temporary changes in the free water level during soaking. As far as could be determined, the water level remained constant during succeeding days of drainage.

The pattern of drainage from the 72 $ft.^3$ of soil over 10 days is illustrated in figure 4. The moisture content at the beginning averaged 40.5 ± 1

Figure 3. --Reconstructed soil model (Phase II) in operation, showing some of the instrumentation used. Upper left, recording soil thermometer; lower left, water level recorder; right, neutron-scattering device for measurement of soil moisture.

percent by volume. Reductions in moisture content were at first rapid, but most rapid at the upper levels. A moisture gradient had developed after 15 hours, with 8 percent more moisture at the 4-foot slope distance than at the 20-foot distance. When the rate of loss from the top began to level off, the two lower positions increased their net rate of loss, reflecting the reduced supply from up-slope. After 48 hours, relative drainage continued fairly constant at all points, but a definite gradient remained up-slope. The pattern indicates that up-slope moisture is continually recharging down-slope storage, which in turn feeds the ground-water table.

A comparison between the 60-cm. tension moisture content and final moisture contents along the column is shown graphically in figure 5. Results are separated into three 6-inch depths at six equidistant stations along the column. Each plotted point represents the percentage of field moisture as a deficit or surplus over the 60-cm. tension value, determined after saturating the sample according to methods described by Hoover, Olson, and Metz (1954). Positive values indicate that the sample in the soil column contained water in excess of 60 cm. of tension, whereas negative values indicate qualitatively the degree of moisture deficit below this tension level. These curves illustrate the existence of different conditions of moisture stress along the slope, as well as with depth below the surface.

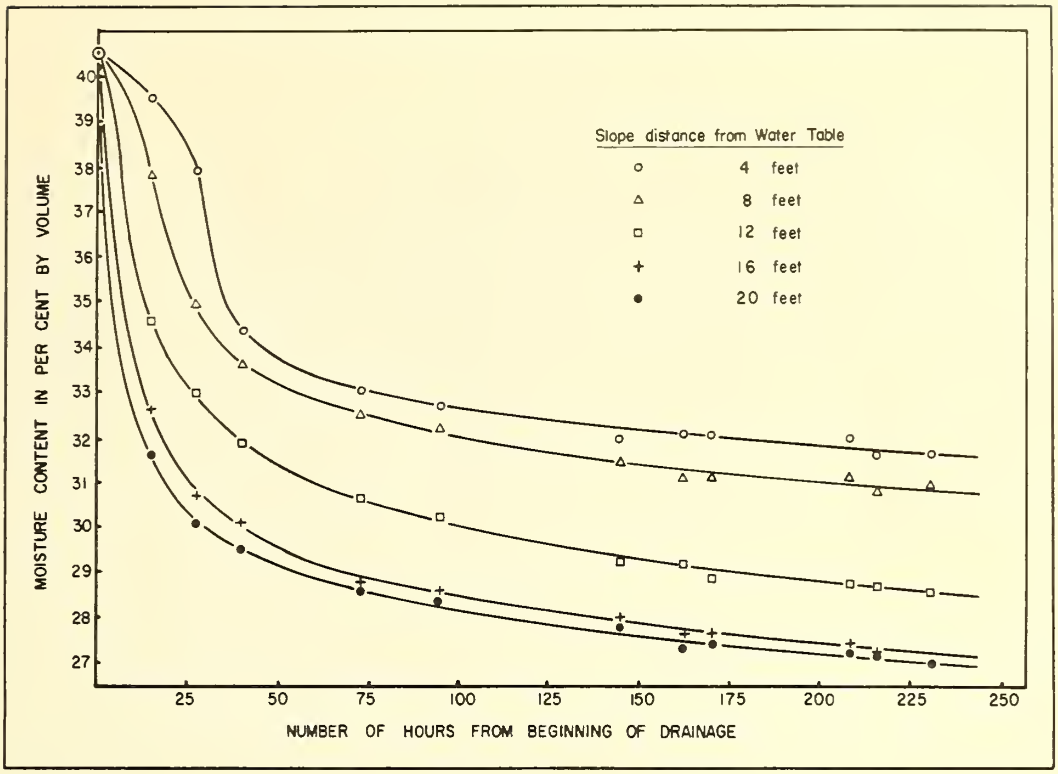

Figure 4.--Soil moisture content at various slope distances from the water table plotted against time since the beginning of drainage, Phase I.

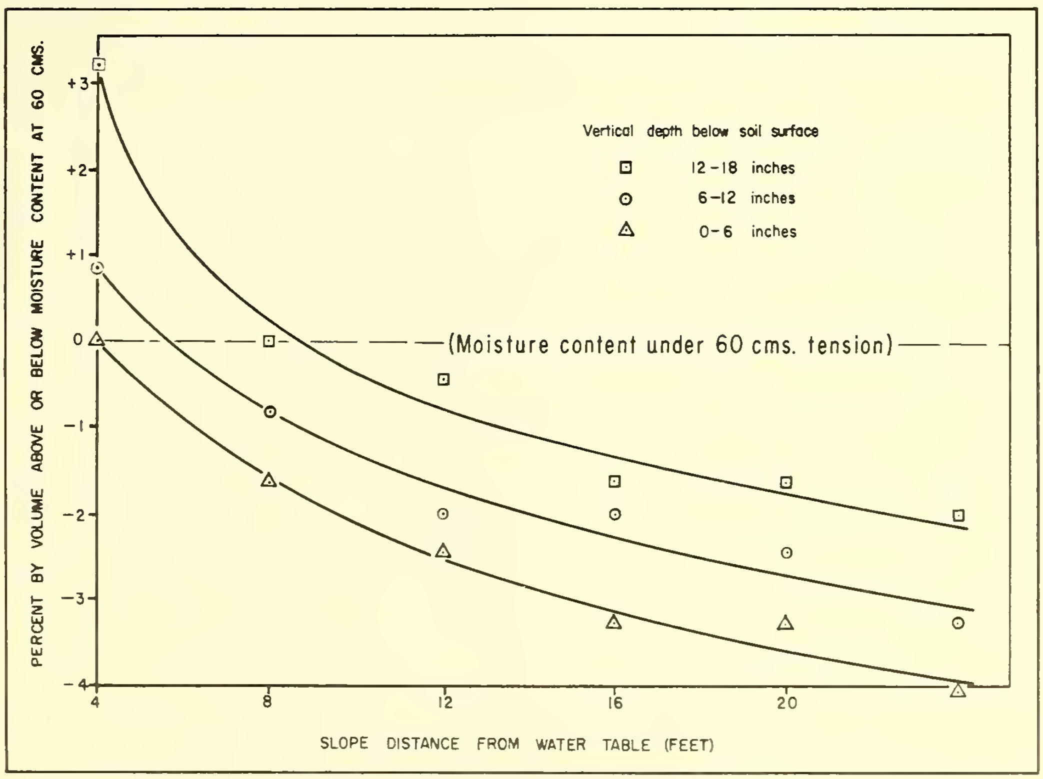

Figure 5.--Comparison between the final moisture content of 18 undisturbed samples from the soil model and their moisture content after equilibration under 60 centimeters of tension, Phase I.

Phase II. The repacked and lengthened model was charged on August 11 and ceased to yield water to the measuring device on October 21. A total of 13.2 $ft.^3$ of water drained from 84 $ft.^3$ of soil during 71 days, of which 2.6 $ft.^3$, or 20 percent, came after 3 days. Only 0.6 cubic foot of water drained during the last 50 days, but, if multiplied by appropriate factors, this discharge is equivalent to about 0.3 $ft.^3/sec./mi.^2$. Such a rate is of the order of magnitude of observed minimum flows from Coweeta watersheds.

Soil moisture contents and tension gradients in the second phase were similar to those in the first phase. However, early discharge of the repacked model was more rapid, the total yield per cubic foot of soaked soil was greater, and the final soil moisture tension gradient was less pronounced than in the first run. Presumably the lower bulk density, and consequently the increased total pore space within the soil, favored more rapid internal drainage as well as reduced moisture gradients up the slope.

Discharge was intermittent after the 30th day, causing some difficulty in securing average rates of outflow during the last half of the drainage period. The average hourly yield from the 1st to the 30th day is plotted in figure 6, showing an approximately linear relationship between the respective logarithms of outflow and elapsed time. These rates of flow are analogous to changes in soil moisture after irrigation found by Ogata and Richards (1957), Nixon and Lawless (1960), and others. Rate of discharge is equivalent to the change in moisture content of the entire column of soil with respect to time (dW/dT), which may be obtained by differentiation of equation 1

$$dW/dT = -abT^{-b-1} \qquad (2)$$

Calculating from the observed rates of drainage plotted in figure 6, equation 2 becomes approximately

$$dW/dT = -0.92T^{-1.68} \qquad (3)$$

where dW/dT is in $ft.^3/hr.$ and T is in days from beginning of drainage.

DISCUSSION AND CONCLUSIONS

It is recognized that not only are actual conditions on watersheds physically different from the artificial soil profile used here but they are subject to additional influences — particularly evapotranspiration. Field demonstration of a persistent tension gradient adjacent to streams is still necessary. However, present results suggest that an analysis of water yield based on negative hydraulic gradients in unsaturated soil may provide a better working hypothesis for studying base flow as well as other hydrograph characteristics in the mountains than the traditional ground-water concept.

From the standpoint of the hydrologist, one of the most fundamental expressions of the relationship of soil to water is contained in the curve which relates moisture content to soil moisture tension. Figure 2 shows the moisture retention of the experimental soil to be linear with the logarithm of tension, at least over the 40- to 15,000-cm. range. Field capacity, always a rather arbitrary value, is reported by various investigators to be from 60 to 350 cm. of moisture tension. It can be seen from the curve that roughly 7 percent moisture by volume (0.84 inch of water per foot of soil depth) is contained within the range of field capacity, to be yielded slowly as tension increases in the soil profile. Thus the persistence of negative hydraulic gradients and their gradual approach to equilibrium can result in a steady accretion to ground water and streamflow from unsaturated soil. Furthermore, there is some evidence from this study that slow drainage will result in gradients in soil moisture stress on natural slopes. Allowing a short period of adjustment following rainfall, a gradual decrease in moisture content with increasing elevation above the stream channel may be expected, and is usually observed on steep slopes. Changes in growth form and a tendency toward xerophytism in vegetation on ridges, even where soil depth is adequate and rainfall superabundant, may be related in part to this gravitational readjustment of soil moisture in mountainous areas.

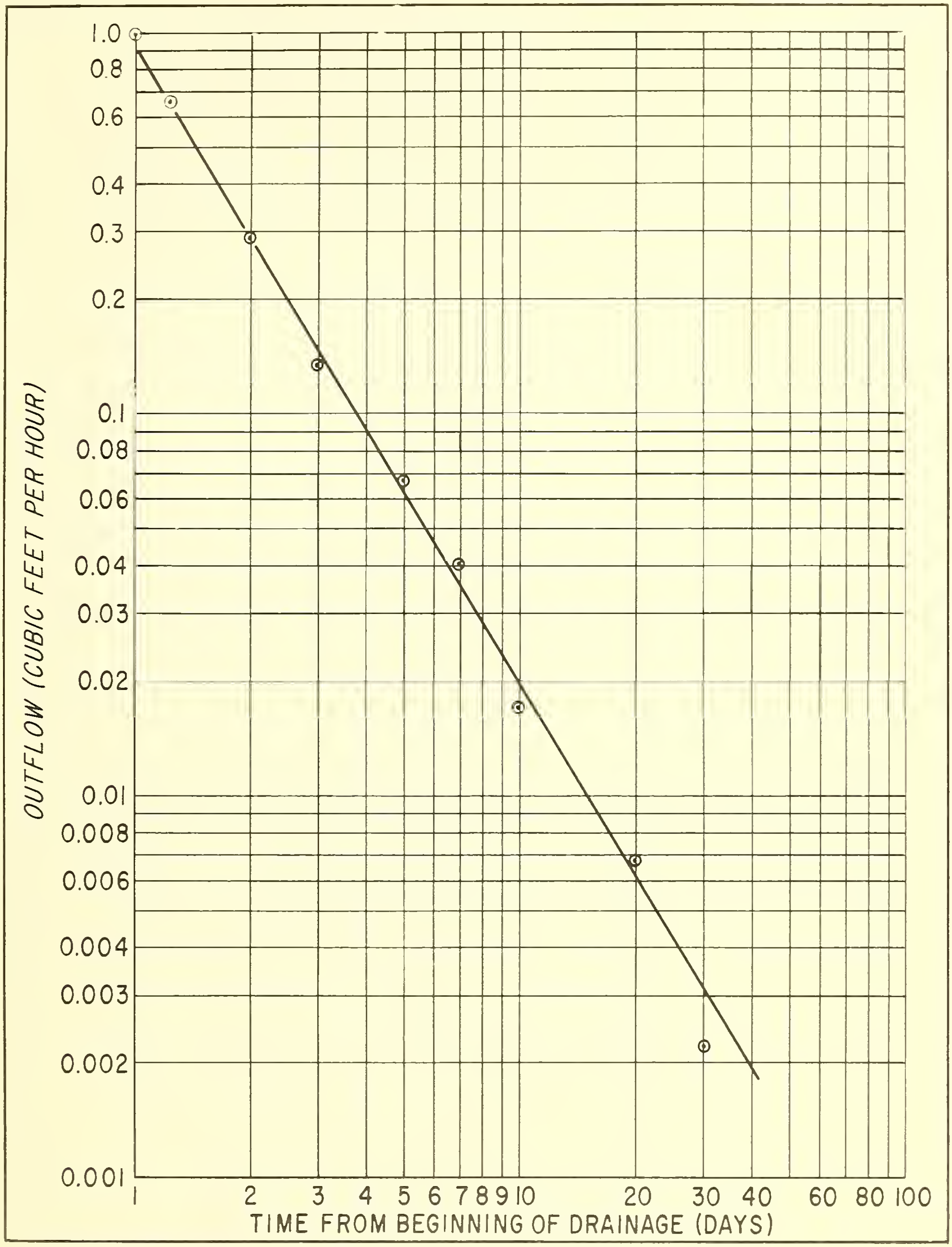

Figure 6. --The relationship between outflow (dW/dT) from the entire soil model, Phase II, to time from beginning of drainage.

Using the artificial soil profile described here, it was found that both changes in moisture content at each level and total outflow agreed closely with the expression developed by Ogata and Richards (1957):

$$W = aT^{-b}$$

Differentiation of this equation gives a similar expression for the rate of drainage. If unsaturated aquifers of small watersheds can be characterized by soil type, size, and elevation above the stream channel, their basic contribution to streamflow under a given rainfall regime might be calculated through a series of such expressions. The integration of rates of unsaturated flow from a watershed will prove to be complex indeed, but the customary explanation of base flow solely in terms of ground-water recession may conceal some of the chief characteristics of stream behavior in steep terrain.

A practical implication of the concept of soil moisture as a source of streamflow concerns the hydrology of headwater regions. Referring to the model, if rain occurs uniformly over the surface of the column after drainage has diminished from a previous soaking, the deficit at the bottom will be quickly satisfied and stormflow will occur. A longer period of time will be required to satisfy deficits farther up-slope, but if rainfall continues, gradual soaking will increase the area contributing to stormflow at the bottom. The tendency, however, should be for up-slope rain to charge the soil mantle in preparation for succeeding days and weeks of base flow, whereas down-slope rain and channel interception will furnish most of the stormflow. The effects of such a system on watershed treatments to stabilize streamflow or increase water yield from steep watersheds may be considerable. For example, recognition that areas immediately adjacent to small streams provide a disproportionate percentage of stormflow may bring about an even greater concern than now exists for the protection of stream environs.

This preliminary study suggests that soil moisture gradients on slopes are partly due to unsaturated flow in response to hydraulic gradients within the soil mass and that these gradients may be sufficient in magnitude to demand consideration in hydrograph analysis, as well as in planning watershed treatments to stabilize or increase water yield. In addition, it seems quite likely that the major source of sustained base flow in Coweeta streams is soil moisture, although some storage undoubtedly exists in saturated ground-water aquifers. A larger experimental soil model is planned, to be equipped with a deeper artificial profile and improved instrumentation, to determine the validity of these initial results.

SUMMARY

At the Coweeta Hydrologic Laboratory the concept of saturated ground-water aquifers does not seem adequate to explain base flow. It is suggested that soil moisture in the range of field capacity is the source of a large percentage of base flow and that moisture is fed down the slope under negative hydraulic gradients.

A 1.5 x 2 x 24-foot soil model was constructed on a 40 percent slope, with an artificial water table at the base. After the soil had been soaked and the surface covered to prevent evaporation, drainage was followed during the next 10 days by neutron-scattering methods for measuring soil moisture. Outflow decreased with time, and the pattern of drainage indicated that it was taking place under tension rather than under positive hydraulic gradients. Actual moisture contents on the tenth day, as determined on undisturbed samples, demonstrated gradients in soil moisture tension both vertically and throughout the 24-foot slope. Moisture contents followed the same trend, showing that at partial equilibrium more water was retained down-slope than up-slope. Measured drainage from a lengthened and repacked model, also covered to prevent evaporation, continued for 71 days, during which the logarithm of the outflow rate was linearly related to the logarithm of time since beginning of drainage.

The mechanism of flow production is discussed, as well as some hydrologic implications of unsaturated flow in sloping soil profiles.

LITERATURE CITED

Edlefsen, N. E., and Bodman, G. B.
1941. Field measurements of water movement through a silt loam soil. Amer. Soc. Agron. Jour. 33: 713-731.

Hoover, M. D., and Hursh, C. R.
1943. Influence of topography and soil-depth on runoff from forest land. Amer. Geophys. Union Trans. 24: 693-697.

Hoover, M. D., Olson, D. F., Jr., and Metz, L. S.
1954. Soil sampling for pore space and percolation. U. S. Forest Serv. Southeast. Forest Expt. Sta. Paper 42, 29 pp.

Hursh, C. R., and Fletcher, P. W.
1942. Soil profile as a natural reservoir. Soil Sci. Soc. Amer. Proc. 7: 480-486.

Meinzer, Oscar E.
1942. Ground water. *In* Hydrology, Vol. IX, Physics of the Earth, pp. 385-443. McGraw-Hill Book Co. New York.

Nielson, D. R., Kirkham, Don, and van Wijk, W. R.
1959. Measuring water stored temporarily above the field moisture capacity. Soil Sci. Soc. Amer. Proc. 23: 408-412.

Nixon, Paul R., and Lawless, G. P.
1960. Translocation of moisture with time in unsaturated soil profiles. Jour. Geophys. Res. 65: 655-661.

Ogata, Gen., and Richards, L. A.
1957. Water content changes following irrigation of bare-field soil that is protected from evaporation. Soil Sci. Soc. Amer. Proc. 21: 355-356.

Remson, Irwin, Randolph, J. R., and Barksdale, H. C.
1960. The zone of aeration and ground-water recharge in sandy sediments at Seabrook, New Jersey. Soil Sci. 89: 145-156.

Richards, L. A., and Weaver, L. R.
1943. Fifteen-atmosphere-percentage as related to the permanent wilting percentage. Soil Sci. 56: 331-339.

Robins, J. S., Pruitt, W. O., and Gardner, W. H.
1954. Unsaturated flow of water in field soils and its effect on soil moisture investigations. Soil Sci. Soc. Amer. Proc. 18: 344-347.