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Moisture and Energy Conditions within a Sloping Soil Mass during Drainage

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Abstract. In an effort to explain the source of nonstorm streamflow in deep-soiled areas of the southern Appalachians, a 3 × 3 × 45-foot inclining concrete trough was constructed on a 40 per cent slope. The structure was packed with a natural sandy-loam soil to a bulk density of 1.3, and after thorough soaking was covered with plastic to prevent evaporation. Outflow was measured at the base, and soil moisture tension and content were recorded for 145 days. As shown by piezometers, the larger pores were substantially emptied in 1.5 days, during which outflow occurred according to the expression,

$$Q = a_1 T^{-b_1}$$

where T is time in days since day zero and a_1 and b_1 are constants. After a 5-day transition period, the logarithm of drainage for the next 80 days was again linearly related to the logarithm of time, but with new constants, a_2 and b_2, expressing unsaturated flow from the entire soil mass. An additional 60 days of flow occurred, deviating more and more from the log-log relation as the limits of drainage were approached. Soil moisture content and tension substantiated the theory that the entire unsaturated soil mass was contributing to outflow throughout the experiment. It is concluded that unsaturated flow in the earth mantle of steep watersheds cannot be ignored in hydrograph analysis, since it may well be a primary mechanism for sustaining baseflow.

Introduction. Increasing concern over water resources has focused attention on how little is known about the source of high-quality surface water from protected mountain watersheds. The generally accepted explanation of nonstorm streamflow (base flow), which accounts for 85 per cent of the yield from many watersheds of the southern Appalachians, assumes that extensive, saturated groundwater aquifers feed streams during nonstorm periods [*Wisler and Brater*, 1959; *Todd*, 1959; *Linsley et al.*, 1958], while stormflow is assumed to come from overland or subsurface flow through interconnecting channels below the soil surface [*Hursh*, 1944]. Although these concepts may apply in many areas, their application in forested mountain land is doubtful.

At the Coweeta Hydrologic Laboratory in western North Carolina, research in the dynamics of baseflow and stormflow is in its fourth year. The experimental basin has steep forested slopes, narrow incised drainage channels, and moderately deep soil over relatively tight granitic country rock. Rainfall averages 80 inches annually but frequent storms produce little or no overland flow. Groundwater wells at Coweeta have generally failed to demonstrate saturated aquifers except along streams and drainageways, where accumulating water appears as spring or seepage flow. Because of the steep topography, such areas are necessarily restricted to the immediate vicinity of the stream, a zone which appears too small to sustain streamflow through the summer period of high evapotranspiration.

In an earlier paper, *Hewlett* [1961] offered an explanation of baseflow which visualizes the entire soil mantle as a storage aquifer feeding sustained flow. In this view, narrow groundwater bodies along stream channels are not of themselves the source but rather a conduit through which slowly draining soil moisture passes to enter the stream. Explanation of the source of baseflow in mountains appears to be chiefly a problem involving the physics of unsaturated flow in soils.

The physics and theory of moisture flow in soil masses of various geometric dimensions and internal structure have progressed in recent years beyond the level available during earlier hy-

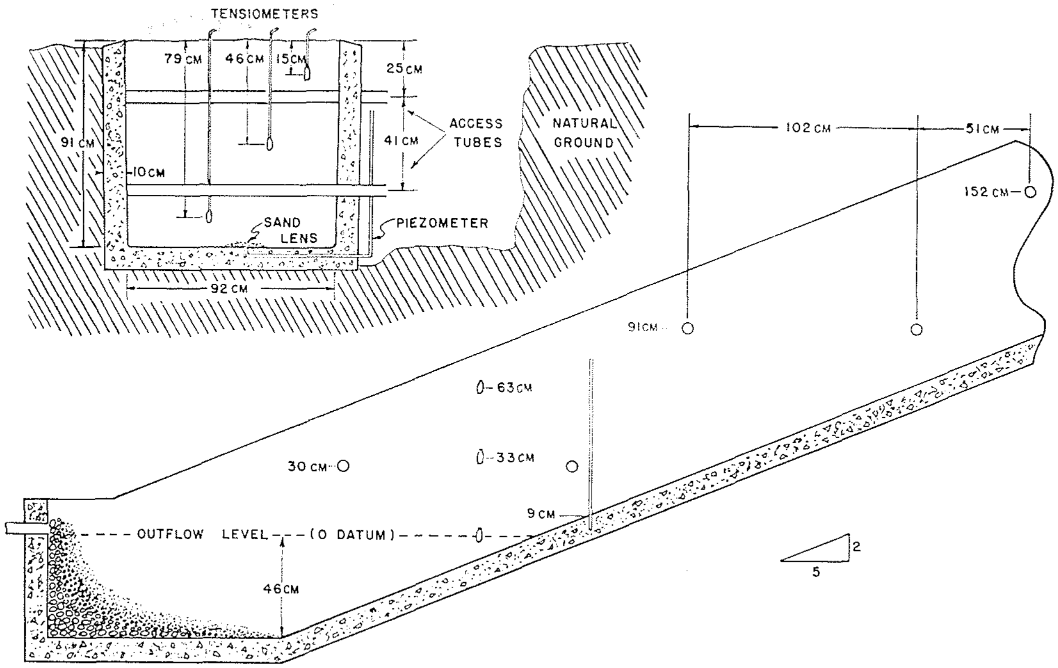

Fig. 1. Cross and longitudinal sections of the lower portion of the inclined soil column. Three additional sets of tensiometers and piezometers are located at 10- to 14-foot intervals upslope. Except where denoted by arrows, numbers indicate vertical distance above the outflow level.

drologic studies. Darcy's familiar equation for flow in saturated systems has been successfully modified to account for flow in unsaturated systems. These equations permit evaluation of moisture conductivity and diffusivity when all boundary conditions and certain physical properties of soil are known. However, as *Gardner* [1959] has pointed out, departures of real systems, particularly those involving nonsteady-state flow, from theoretical solutions indicate the importance of various natural inhomogeneities that are difficult to account for theoretically. The physics of moisture movement in soil offers a firm basis for hydrograph theories but it is doubtful that we are yet finished with field observation and model testing as a means of closing the gap between physical theory and hydrologic application.

Seeking to explain further the source of non-storm streamflow from the slopes of the southern Appalachians, a series of inclined soil models, thought to approximate the geometry of segments of natural watersheds, have been constructed at Coweeta. *Hewlett* [1961] reported early experience with two sloping, open-topped columns, 24 and 32 feet long. These structures, when artificially soaked, produced measurable outflow for more than 2 months without further recharge. This paper deals with a larger, better-instrumented model designed to clarify the moisture and energy conditions within sloping soil profiles during drainage. Results are believed to have general application to hydrologic theory of water yield from steep land.

Methods. An inclining concrete trough measuring $3 \times 3 \times 45$ feet was constructed on a 40 per cent slope (Figure 1) and packed with well-mixed natural soil to a bulk density of 1.3 ± 0.1. The soil was excavated nearby from the C horizon of Halewood sandy loam, a common type in the southern Appalachians. Texture analysis by the Bouyoucos hydrometer method averaged 60 per cent sand, 18 per cent silt, and 22 per cent clay. Total pore space in the packed condition was about 50 per cent by volume, very close to that in its normal undisturbed state.

After a sprinkling system had soaked the inclined surface for several days, the structure

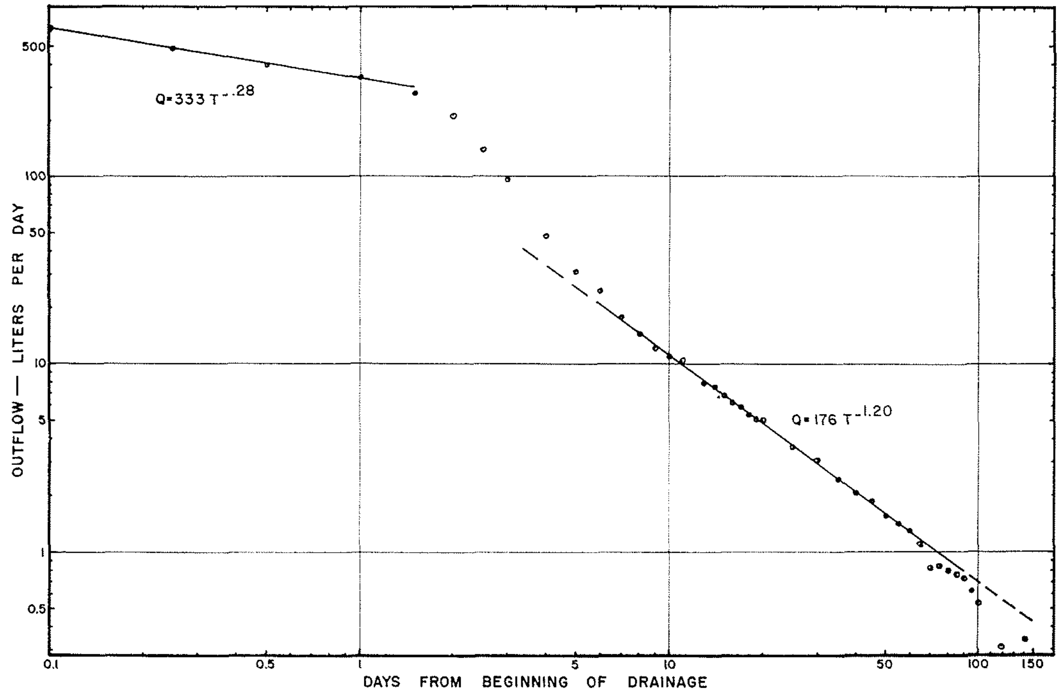

Fig. 2. Outflow since beginning of drainage, showing log-log relation to time.

was covered with plastic film and allowed to drain. Outflow was measured continuously by a water level recorder mounted on a tank at the base of the column. The outflow pipe established a free water surface which was used as the zero datum for all measurements. The soil under the free water surface was graded to sand, gravel, and rock to simulate stream bank conditions and to allow free drainage.

Seventeen access tubes to permit measurement of soil moisture by the neutron scattering method were inserted horizontally through holes in the concrete wall at various levels up the slope. In addition, there were four sets of one piezometer and three tensiometers distributed up the slope. The first tensiometer cup was located at the outflow level, or 0 cm, the first piezometer at 9 cm vertically above zero datum, the first access tubes at 30 cm, and so on up the column.

The soil was soaked on July 6, and soil moisture tension and content were recorded at first hourly, then daily, and finally weekly as the drainage rate decreased. Soil temperature and barometric pressure were recorded for the duration of the experiment.

Results. After 145 days of outflow, the experiment was terminated on November 30, 1960, and another phase of the study was begun. A total of 1.26 m^3 of water drained from 10.85 m^3 of soil above the outflow level, 76 per cent during the first 5 days, 19 per cent during the next 45 days, and 5 per cent during the last 95 days. Outflow fluctuated in a cyclic manner with temperature and barometric pressure changes, but these fluctuations were traced mainly to the influence of gases trapped within the soil below the outflow level. When averaged from week to week, outflow rate decreased smoothly with time. In Figure 2, outflow is plotted over time from beginning of drainage; both are plotted on logarithmic scales because experience has shown that the logarithm of unsaturated drainage tends to be linearly related to the logarithm of time [cf. *Ogata and Richards*, 1957; *Nixon and Lawless*, 1960]. This drainage trial, as well as replicated trials later on, tended to show two separate periods during which the log-log relation of outflow to time was linear. During the first 36 hours, while the saturated portion of the model drained rapidly, outflow could be

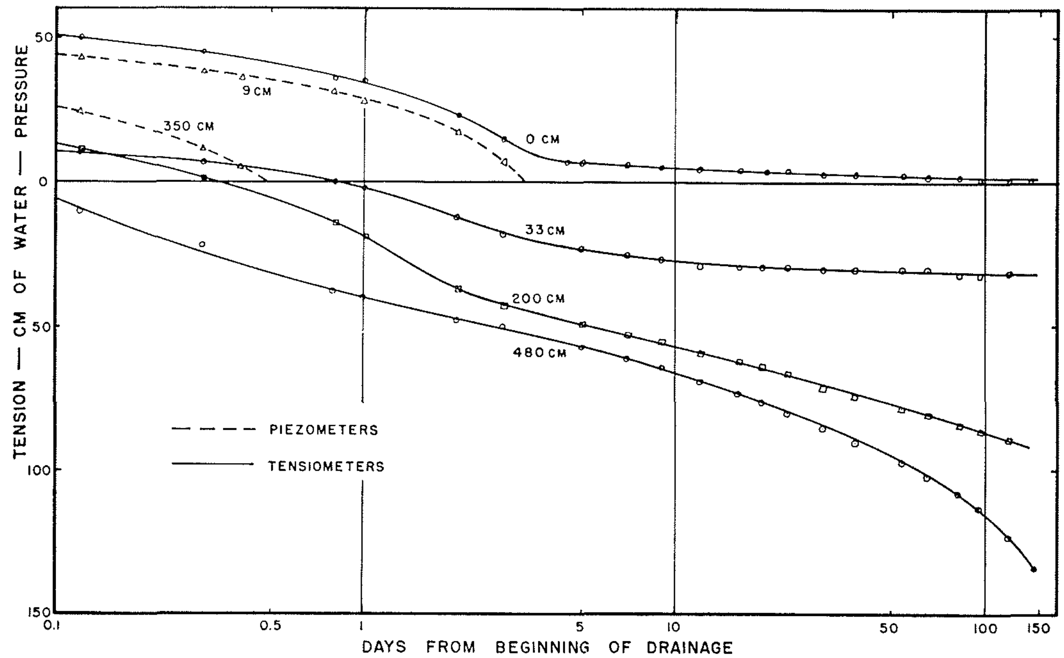

Fig. 3. Changes in pressure and tension at selected levels within the soil mass.

accurately expressed as

$$Q = a_1 T^{-b_1} \qquad (1)$$

where Q is the rate of outflow, T is time elapsed, and a_1 and b_1 are constants peculiar to the system. After a 5-day transition period, during which the larger pores of the soil mass above the outflow level were substantially emptied, the logarithm of outflow was again linearly related to the logarithm of time, but with new constants,

$$Q = a_2 T^{-b_2} \qquad (2)$$

Outflow during the last 60 days was intermittent, and it deviated more and more from equation 2 as the weather grew colder and various limitations of the system became significant.

Records from selected tensiometers and piezometers which are plotted in Figure 3 allow comparison of outflow rates to energy conditions (or matric potential) within the draining soil mass. The two major periods of drainage illustrated by equations 1 and 2 are associated respectively with saturated and unsaturated flow. During the first 36 hours, emptying of the larger soil pores masked unsaturated flow from the remainder of the soil mass, both as to amount and rate of delivery to the outflow pipe. As the free water surface retreated toward the zero datum (piezometers at 350- and 9-cm levels in Figure 3) a transitional period began and continued until about the fifth day, when all larger pores were drained. However, nearly all drainage after 36 hours was derived from the entire mass of unsaturated soil as indicated by increases in soil moisture tension at 33, 200, and 480 cm above the zero datum. There was no doubt that unsaturated conditions prevailed along the concrete bottom of the trough after the first 2 or 3 days, since piezometers were sucked dry (see Figure 1) as the free water surface passed downward.

Theoretically, at least, the soil moisture tension at any point within the model (neglecting osmotic forces) is approaching a value equivalent to the height above zero datum. Thus the tension in centimeters of water should approach the vertical distance above the outflow in centimeters. In Figure 4 the tension at 15 and 79 cm below the sloping soil surface at each of four sets of tensiometers up the slope is plotted over the vertical height above the outflow level. The data are plotted for 7 and 119 days from the beginning of drainage and the curves are shown

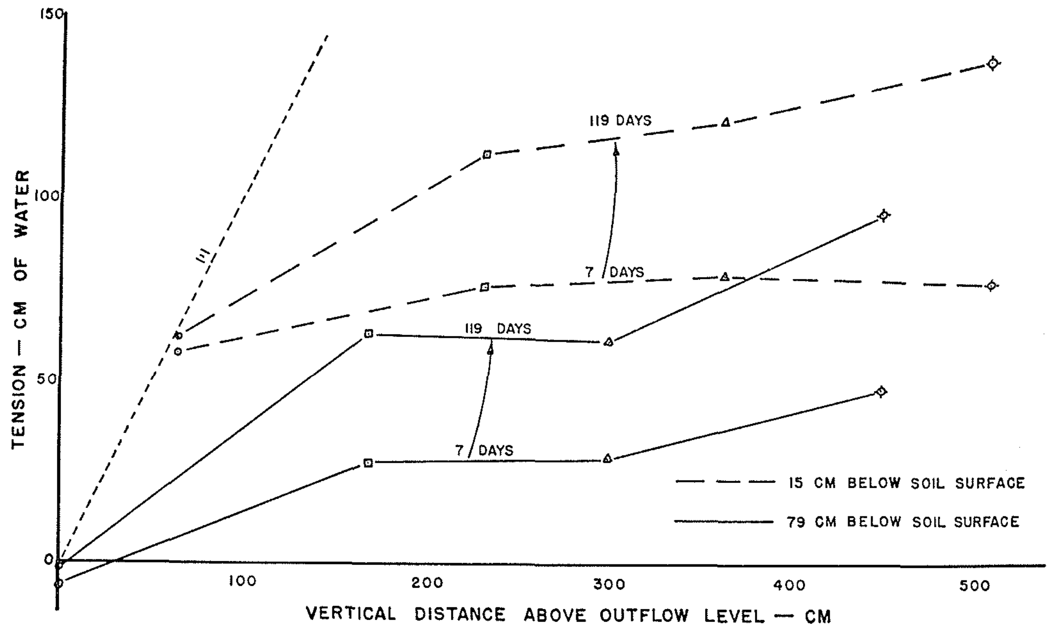

Fig. 4. Soil moisture tension increases with time and elevation above the outflow level, and decreases with depth below the soil surface.

rotating toward the 1:1 ratio of tension to height. Within each vertical profile, viewed apart from the whole structure, soil moisture tension reacts quickly to approximate a 1:1 ratio with height. Thus the difference between the 15- and 79-cm levels is roughly 64 cm all the way up the slope. However, local tension reacts more slowly to the remote datum at the outflow level. Nevertheless, all values appear to be rotating toward eventual equilibrium at the 1:1 ratio of height to tension, again neglecting possible osmotic forces. Time and elevation are shown to be factors affecting the development of tension within a draining soil mass that is protected from evaporation. Changes in the angle of slope and the physical properties of the soil may be expected to play a similar role.

Neutron meter records of soil moisture permitted quantitative determination of the source of the outflow. Moisture-content changes within the whole structure were substantially equivalent to outflow except during early drainage. Outflow exceeded soil moisture change by 31 per cent during the first 10 days. During this time, moisture concentration along the floor of the model was poorly reflected in neutron meter counts because of the location of the access tubes. After the tenth day, moisture change was well correlated with outflow. Moisture content is plotted over time in Figure 5 for the selected levels, 30, 152, and 460 cm above zero datum. The data show some scatter, but the trends are clear enough. No important change occurred in moisture content 30 cm above the outflow level. At other levels the logarithm of moisture content decreased linearly with the logarithm of time, and the sum of all changes (Q) within the draining soil mass is similarly related to time, as in equations 1 and 2. Although the data varied because of deviations in soil compaction from place to place, both the total amount of moisture drained and the rate of drainage appeared to increase with height above the outflow level.

One year later, during the summer of 1961, the whole experiment was repeated with the same structure in order to determine if weathering of the soil was affecting the results. Moisture, energy conditions, and outflow rates were virtually identical during the second experiment.

Discussion and conclusions. Soil within and below the zone of tree roots but above bedrock or a water table, when recharged regularly by

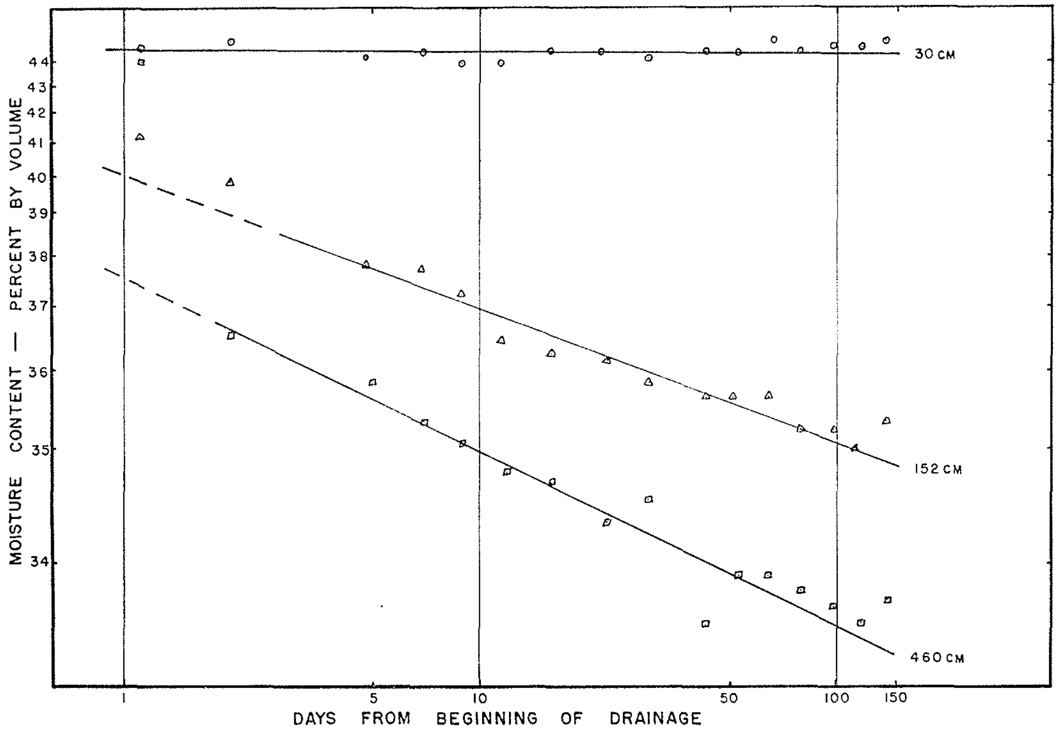

Fig. 5. Moisture content decreases with time and elevation above the outflow level.

rainfall, may constitute the chief aquifer for stored water between rains in steep terrain. *Meinzer* [1942] has referred to this zone as the 'no man's land of hydrology,' adding that water in it was to a large extent in 'dead storage.' A more realistic definition of this reservoir may be 'dynamic storage,' and, in addition to the saturated aquifers which lie below, it should be recognized as the location of important supplies of potential stream water in many areas.

Knowing where water is and how fast it is moving underlies all efforts to manage the supply. The behavior of water within the soil mass used in this study can probably be predicted by solution of the flow equation if boundary conditions are adequately defined. Definition of a natural system is possible only in general terms at present, however, because of the irregular geometry of soil masses, soil physical properties, and fluctuating rainfall. We can, of course, record outflow from a watershed, but there is a real need for improved concepts for determining the source and timing of flow by the study of the morphology of drainages. From such knowledge, watersheds can be evaluated as moderators of water flow, and future behavior under specified conditions may be predicted with greater precision. The flow equation or its modifications probably affords the best basis for hydrograph analysis and correlation of drainage morphology to outflow.

Despite differences in the size and morphology between a watershed and the soil model, the relative rates and amounts of drainage of saturated and unsaturated soil observed here, particularly when reinforced by extensive measurement of soil moisture on the Coweeta basin, lead us to conclude that unsaturated flow in mountain soils is both an important and an immediate cause of sustained baseflow in mountain streams. Even after 2 months of drainage, 10.85 m^3 of unsaturated sandy loam soil was yielding 1.42 liters of water per day. Multiplying by appropriate factors, which are, of course, rather speculative because of the lack of good estimates of total soil volumes, shows such yield to be within the order of magnitude of low flows from Coweeta watersheds, despite the fact that 2 months without recharge is an extremely rare event at Coweeta.

It is interesting to speculate whether the simplified empirical flow equations (1 and 2) are fundamental to movement of water through many soils under gravity. If so, such equations may prove to be useful tools in hydrograph analysis, since water in streams must be the sum of a series of similar components of flow. Evaluation of the parameters a and b for each soil type and drainage geometry should help to explain why watersheds which look similar often yield quite differently. Unit watershed experiments at Coweeta and comparable experiments elsewhere have brought many such differences to light [*Hewlett and Hibbert,* 1961].

Work with models and small watersheds is continuing at Coweeta in an effort to define the behavior of water in soil, particularly as its behavior affects the timing of baseflow and stormflow from mountain watersheds. It is odd to note that, whereas baseflow from the watershed model was derived from unsaturated soil, the part of flow most equivalent to stormflow came from 'groundwater' drainage. Certainly, in conventional methods of hydrograph separation this possibility is not recognized in some areas, since storm runoff is related almost by definition to overland flow and channel interception. Field observations at Coweeta suggest that stormflow may well be associated with temporary expansion of saturated aquifers along stream channels—aquifers which deplete rapidly through porous material on steep slopes. A soil model measuring $5 \times 7 \times 200$ feet is under construction at Coweeta so that we can study the source and timing of baseflow and stormflow under natural rainfall. Mathematical models of flow will be tested on this structure and compared with adjacent gaged watersheds.

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