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The Role of Soil Water in the Hydrologic Behavior of Upland Basins[1]

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ABSTRACT

The distribution of soil water in upland basins greatly affects the extent of source areas and the response patterns of both storm and between-storm streamflow. Except during the most extreme storms, all the precipitation falling on well-vegetated slopes infiltrates and while some reappears in the channel as stormflow, a major portion of the rain remains in the basin as dynamic storage. During a storm, the stormflow source area expands out from the stream channel as slopes contribute primarily unsaturated subsurface flow and the channel system lengthens. After the storm ceases, source areas may continue to expand as subsurface flow feeds the lower slopes near the channel, often leading to a second hydrograph peak several hours or days after the rain ceases. As the channel system and source areas recede, unsaturated subsurface flow continues to sustain baseflow. Basin parameters that affect the soil water regime and associated soil water energy conditions, and therefore the distribution of source areas, are slope length from channel to ridge, angle of slope, regolith depth, and regolith physical properties. Physical models of hillslope segments have provided some insight into the interrelations among the basin parameters as well as the flow pathways and source areas of subsurface flow.

INTRODUCTION

The fact that soil water conditions may influence the hydrologic behavior of watersheds is well recognized. Yet efforts to translate this knowledge into a working model describing the various sources, pathways, mechanisms, and timing delays that underlie the dynamics of stream discharge from headwater basins have met with little success. One of the primary reasons for this failure has been the explanation of the storm runoff process almost entirely in terms of overland flow. On permeable upland slopes in humid regions, overland flow is rarely observed and subsurface flow in the vicinity of the stream channel accounts for much of the storm runoff (stormflow). Important to

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the subsurface flow process, and watershed behavior in general, are the basin's physical characteristics. These characteristics will affect the distribution and flow pathways of water in the soil mantle and the timing of flow from the stormflow source areas to the channel.

To understand why so little emphasis has been placed on the role of soil water in the hydrologic behavior of basins we must first review briefly some recent history of hydrology. The work of Robert E. Horton (1945), a geomorphologist and hydrologist in the 1930's and 1940's, placed considerable emphasis on the role of infiltration and surface soil erosion on the development of stream channel patterns by overland flow. Horton's work implied that rainfall exceeding the infiltration capacity, of rainfall excess, caused overland flow and was responsible for the immediate stormflow responses in the channel system. Following the work of Horton, a "technology of overland flow" developed and very little emphasis was placed on the more critical "basin-wide" infiltration process. Attention was focused on overland flow as the predominant hydrologic process to the extent that all other processes were virtually ignored. Subsurface flow (sometimes referred to as interflow and quick return flow) was considered to move at velocities too slow to become part of the stormflow hydrograph and consequently was largely ignored as an important hydrologic process. As a result, hydrology has been "surface process" oriented and the mechanisms and pathways of water movement through the soil profile have received little attention by hydrologists.

Horton's infiltration model and subsequent flow models have been modified to a certain degree, but most still rely on overland flow as the primary source of stormflow, consequently forcing virtually all subsurface flow into overland pathways. Within the past 10 years a few hydrologists have questioned the validity of the overland flow model as applicable to humid region vegetated basins. This has led to a greater emphasis placed on the movement of soil water and source areas of streamflow during both storm and between-storm periods (Hewlett & Hibbert, 1967; Kirkby & Chorley, 1967; Betson & Marius, 1969; Hewlett & Nutter, 1970; Ragan, undated). In actuality, the overland flow model is just one end member of a spectrum of possible flow models. An entirely subsurface flow model would represent the other end member. The overland flow models seem best suited to the domain of basins where rainfall intensities are very high and vegetation sparse. On the other hand, in well-vegetated basins the operational flow models would be closer to the subsurface flow end of the spectrum.

To avoid misunderstanding, overland flow is defined as rainwater that fails to infiltrate the soil surface at any point along its way from the basin surface to the stream channel. This definition is necessary to separate, for the purposes of this discussion, the rapid delivery of overland flow to the stream channel from the much slower delivery of subsurface flow. Overland flow may move at velocities up to a 8 cm/sec, more than 6,000 m/day, whereas subsurface velocities at saturation seldom exceed 4 cm/day. Rainwater that infiltrates and later seeps out only a meter downslope has already been delayed long enough at these velocities to alter the characteristics of the stormflow hydrograph. This fine line of distinction is important because whether water has infiltrated and moved only a meter before appearing as a surface extension of the channel system or whether it has not infiltrated at all has a great deal to do with the nature of a basin's hydrologic behavior.

Forest hydrologists are well aware that overland flow occurs rarely or in very small amounts from forests and many wildlands. This is not so strange to anyone who has stood on vegetated slopes during downpours and, after watching all the water enter the soil, has later seen it seep into the stream channel. In addition, the entire basin is not contributing equally to stormflow. In other words, depending on antecedent conditions and physical characteristics of the basin, various portions of a basin may respond differently to rainfall input by contributing variable quantities of stormflow to the stream channel, not only during the storm itself but for considerable periods of time following the storm. Thus, some areas of the basin contribute more stormflow than others and it is conceivable that some portions of a basin contribute stormflow only during the most extreme storms (Betson & Marius, 1969; Hewlett & Hibbert, 1967; Dickinson & Whiteley, 1970; Ragan, undated).

In conclusion, infiltration as a critical hydrologic process is frequently not a limiting factor in humid region well-vegetated basins when the total mosaic of vegetation patterns and basin shape is considered. Infiltration capacities may be momentarily exceeded during an intense burst of rain but most of this excess rainfall is ponded or infiltrates the soil and never reaches the stream channel as overland flow. Average infiltration over a basin under natural rainfall is quite different from plot infiltration capacities determined by rainfall simulators or similar techniques. Infiltration capacity curves drawn under such conditions can rarely be used to predict the infiltration excess and stormflow during natural storms.

SLOPE WATER MOVEMENT

Hoover and Hursh (1943) and Roessel (1950) first focused attention on the importance of slope water movement in the hydrology of upland forested basins. However, it was almost 20 years before Hewlett (1961b) reported the results of a hillslope drainage study that presented strong evidence that the storage and movement of soil water on slopes predominantly influenced the stormflow and baseflow characteristics of a basin. It was apparent from the hillslope study and others to follow that the important physical characteristics of a basin controlling the water and energy conditions and the rate and source of outflow from a draining slope were (i) angle and length of slope and (ii) depth and physical properties of the hydrologically active portions of the soil mantle or regolith (Hewlett & Hibbert, 1963; Whipkey, 1967; Troendle, 1970).

Occurrence in Hillslope Segments

The last of four hillslope models constructed at the U. S. Forest Service Coweeta Hydrologic Laboratory, Franklin, North Carolina, was 61 m long, 2.1 m deep, and 1.2 m wide on a natural 35% slope packed with soil to as uniform a density as possible. In essence, the model provided a nearly isotropic hillslope segment roughly half the average length of slopes in the Southern Appalachian mountains. Impermeable segment sides and bottom were formed with several layers of plastic and an outflow pipe in a headwall at the lower end permitted manipulation of water table level and continuous measurement of outflow. Overland flow was measured with an outflow pipe at the top of the wall, but after grass covered the soil there was no overland flow. At no time in over 7 years of operation did the water table emerge through the soil surface nor did drainage cease. Volumetric water contents and soil water pressures in the segment were monitored with a neutron scattering device and tensiometers, respectively.

Comparison of discharge hydrographs from the hillslope segment and the 15-ha watershed on which it was built are shown in Fig. 1 and 2. A 101-mm (3.96-inch) September 1963 storm (Fig. 1) on well-drained soils partially dried by evapotranspiration demonstrates how quickly subsurface flow can appear as outflow. The main portion of the storm ended shortly before the major stormflow peak at 16 hours, although a short burst of rainfall caused

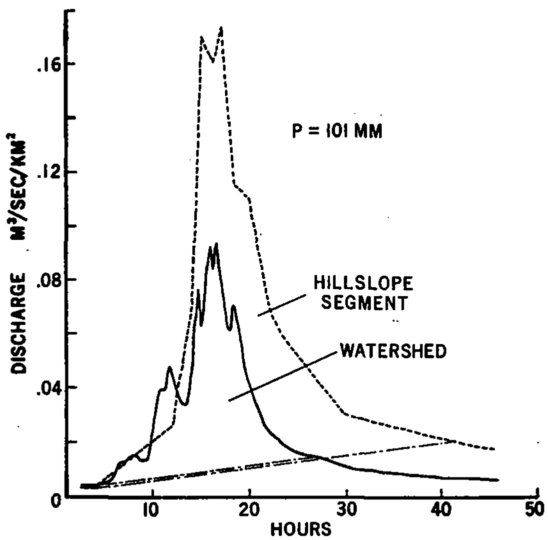

Figure 1. Comparison of outflow from the 61-m long hillslope segment and its companion 15-ha watershed following a 101-mm storm in September 1963. Stormflow is arbitrarily separated from baseflow by a straight line.

another small peak at 18 hours. The 61-m segment produced an almost simultaneous hydrograph peak twice as high as the watershed's peak and a stormflow duration half again as long. [Stormflow is arbitrarily separated from baseflow by a straight line with a slope of 5 X 10^{-4} m^3 sec^{-1} km^{-2} $hour^{-1}$, (Hewlett and Hibbert, 1967)]. The segment had no active channel at any time during the stormflow period and all outflow was the result of subsurface flow. Although the rain was sufficient to produce high water contents well up the slope of the model, outflow receded rapidly.

The watershed reveals its greater depth and length of slope by storing a larger proportion of the rain and by dropping its rate of discharge even more rapidly. In terms of volume of stormflow produced, the watershed yielded 2% of the rain received and the hillslope segment yielded 5%. Included in the watershed yield is the rain falling directly into the channel, or channel precipitation. Considering the absence of overland flow and the behavior of the segment during this storm, it can be concluded that only a narrow zone, or source area, along the channel yielded subsurface flow to the channel system.

During an even larger storm of 143 mm (5.63 inches) in September 1965, (Fig. 2) the watershed yielded a substantial peak, stored 94% of the rain, and dropped rapidly back to normal flow. Most of the storm's rainfall occurred during two sustained periods, corresponding to the two peaks in watershed outflow. No rain occurred after the last peak. Again only a small portion of the total watershed area, primarily the near-channel areas, yielded stormflow. The segment produced about the same peak flow as before (perhaps near the upper limit of the segment to produce water) and although stormflow continued for 5 days at a well-sustained rate, about 80% of the rain remained in the segment after stormflow ended. Again, there was no

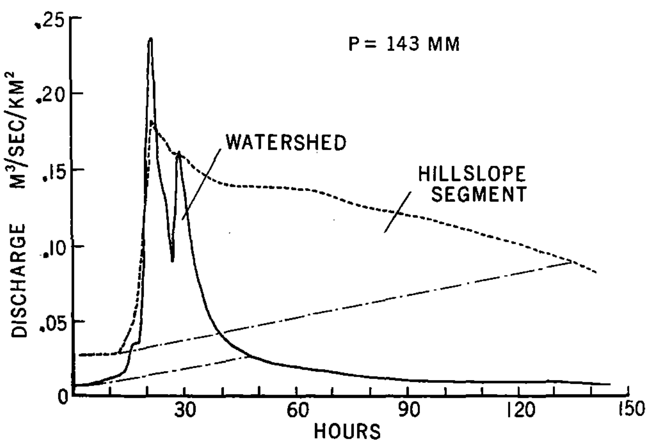

Figure 2. Comparison of outflow from the 61-m long hillslope segment and its companion 15-ha watershed following a 143-mm storm in September 1965. Stormflow is arbitrarily separated from baseflow by a straight line.

overland flow or an active channel in the segment at any time during the stormflow period.

As water was fed to the water table during the storm, not only from soil directly above but also laterally from upslope, the water table rose and the effective storage depth at the lower end of the segment was reduced. However, storage was still adequate because the downslope subsurface travel time served as a form of dynamic storage. The surprisingly well-sustained rate of outflow was the result of (i) the water table receding and (ii) unsaturated flow from the lower two-thirds of the slope. In essence, the stormflow source area expanded upslope during and for a short time after the storm and then slowly receded downslope during the period of sustained outflow. The watershed again exhibited its greater depth, on the average two to three times the segment's depth, and its greater slope length by storing more of the rainfall. It required a 500-mm (20-inch) rainstorm of 3 day's duration to force the watershed to deliver 20% of the rainfall as stormflow and to behave as the segment did in this 143-mm storm.

The previous two examples illustrate slope water movement during and following rainfall. Consider now the gradual redistribution of water in a hillslope segment with evapotranspiration prevented. An earlier hillslope segment built at Coweeta, North Carolina and reported by Hewlett and Hibbert

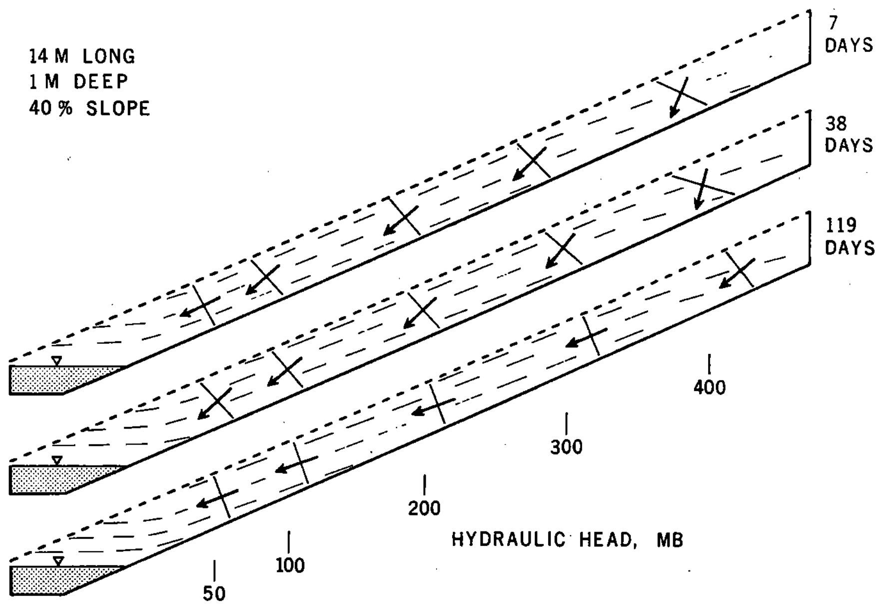

Figure 3. A drainage sequence of the covered 14-m long hillslope segment illustrating the reorientation and direction of flow lines during drainage. The dashed lines represent isolines of matric suction measured at four vertical banks of tensiometers. The first dashed line above the water table represents −25 mbars and each additional line represents an increment of −25 mbars. Flow directions are shown by the arrows.

(1963) was 0.9 m deep, 0.9 m wide, and 13.7 m long on a 40% slope. The segment consisted of a concrete trough packed with a sandy loam soil to a relatively uniform bulk density. After construction, the segment was thoroughly soaked and covered to prevent evaporation and further wetting by rainfall. A sequence of soil water energy conditions within the segment during drainage is shown in Fig. 3. Isolines of matric suction and hydraulic head and the resulting flow lines are shown at intervals of 7, 38, and 119 days after drainage began. The average water content after soaking was approximately 40% by volume and at the end of the drainage cycle was approixmately 34%.

At the beginning of the drainage cycle when the soil mass was wet, the actual flow direction was oriented towards the bottom, although the net flow was downslope. As drainage continued the flow lines slowly oriented parallel with the surface. Whisler (1969) reported a similar flow pattern for a theoretical analog model under steady-state flow conditions. Similar energy and flow-line patterns have been observed in the laboratory on a variable slope model that is 6 m long, 1.5 m deep, and 0.2 m wide. This segment model is designed to study the interrelationships among various physical characteristics of slopes, the physics of unsaturated water movement in large soil masses, and problems associated with scaling flow models.

The preceding example of a covered hillslope segment perhaps best illustrates the drainage of deep subsoil horizons where there is little withdrawal of water by plant roots. Figure 4 shows how the energy gradients and flow lines would appear in relatively isotropic surface horizons during a period of evapotranspiration and rainfall. The energy gradients and flow lines

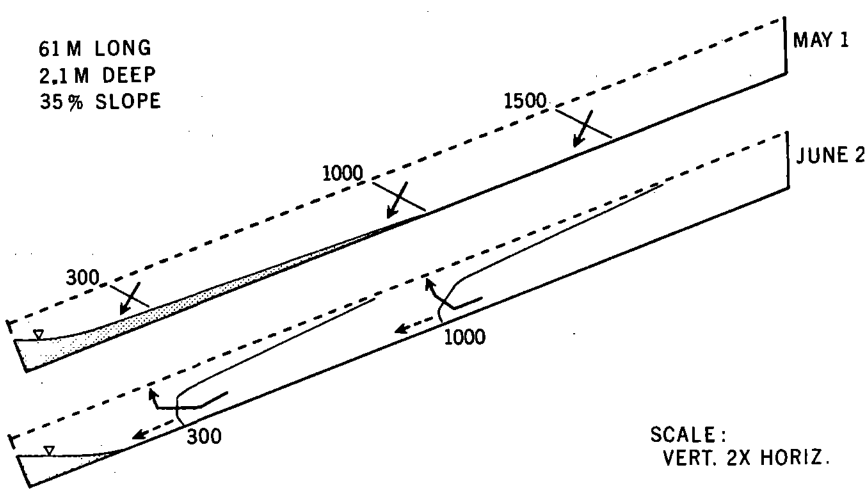

Figure 4. A drainage sequence on the grass-covered 61-m long hillslope segment illustrating the reorientation and direction of flow lines during a period of drainage and evapotranspiration. The numbers represent the hydraulic head in mbars. Flow directions are shown by the arrows.

in the 61-m long hillslope segment at Coweeta, North Carolina, are shown for the period 1 May, following a soaking rain, to 2 June while the segment was in grass cover. At the beginning of the period the flow lines resemble the initial wet stage of Fig. 3. However, as drainage continues and the surface meter of soil is dried by evapotranspiration, the general flow pattern remains laterally downslope, although a considerable portion of the water is directed to the surface under energy gradients created by evapotranspiration. At no time during this 1-month period, or for the remainder of the growing season, did outflow cease. We could expect similar conditions to exist on natural hillslopes leading to dry upper slopes and wet lower slopes as water slowly migrates downslope. Thus, in the advent of a storm, the lower slopes will respond more quickly and produce outflow rapidly enough to become stormflow. The mechanics of stormflow production may be viewed as a relaxation of the energy gradients upslope as the storm continues. The response of this relaxation will vary with rainfall intensities, antecedent conditions, and basin physical characteristics.

Although these results were obtained for hillslope segments with relatively isotropic soil and an impermeable artificial bottom, there is evidence that similar lateral flow conditions exist on natural slopes. Minshall and Jamison (1965) report similar results on slopes with claypan soils. Zaslavsky and Rogowski (1969) present a general model on how subsurface movement of water might contribute to the formation of soil horizons on slopes. They conclude that the magnitude and direction of soil water movement will depend on the degree of anisotropy and slope of the soil mass.

Occurrence in Watersheds

Field evidence of the magnitude of lateral soil water movement over a 24-ha Whitehall Forest Experimental Watershed in the Georgia Piedmont has been presented by Tischendorf (W. G. Tischendorf, 1969. Tracing stormflow to varying source areas in a small, forested watershed in the Southeastern Piedmont. Ph.D. Dissertation. University of Georgia, Athens). Characteristic of the Piedmont is a horizon of restricted permeability approximately 1 to 2 m below the surface. As a result, a considerable portion of the annual basin discharge results from lateral movement of water in the unsaturated phase in the upper soil horizons. Three years of soil water data gathered from throughout the basin were summarized into soil water prediction equations for slope position and time of year. Combining all slope positions throughout the basin, the departure of the soil water content from the annual mean at various depths to 6 m is presented in Fig. 5. The annual maximum and minimum soil water contents in the surface 0.5 m of soil are coincident with the spring and fall equinoxes, respectively. As shown in Fig. 5, the yearly maximum and minimum water contents at greater depths are both lagged and damped with increasing depth. At 6 m there is little change in annual soil water content. Collaborating this evidence are the relatively minor

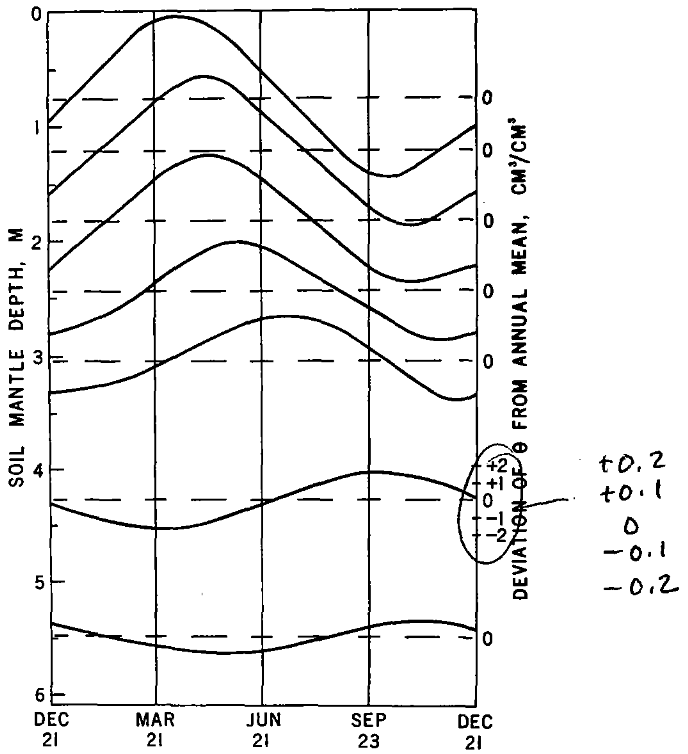

Figure 5. The deviation of water content by volume (Θ) from the annual mean as a function of depth for the Whitehall Forest Experimental Watershed in the Georgia Piedmont.

seasonal ground-water fluctuations, indicating a rather constant recharge to and discharge from the ground-water aquifers.

The main ground-water table in the Whitehall basin occurs at a depth of 10 to 15 m. Over 5 years of streamflow data indicate that baseflow from the saturated zones is rather constant throughout the year, averaging about 20% of the total annual streamflow. In the absence of overland flow, much of the remaining 80% of annual streamflow is the result of subsurface flow downslope to the channel system. Of this 80%, half leaves the basin as stormflow and half as baseflow. When a diagram similar to Fig. 5 is drawn for each of the major slope positions, lower, mid, and upper slope, a somewhat more rapid penetration of the annual recharge wave is evident for the lower slope positions than for the upper slopes. This result is to be expected because of the additional water moving laterally downslope and collecting in the lower slope positions. During the year, there is a relatively constant rate of flow through the impeding horizon into deeper soil while most of the water from large rainstorms is diverted laterally downslope.

The preceding examples show the importance of water movement in the soil mantle, particularly the surface horizons, to the hydrologic behavior

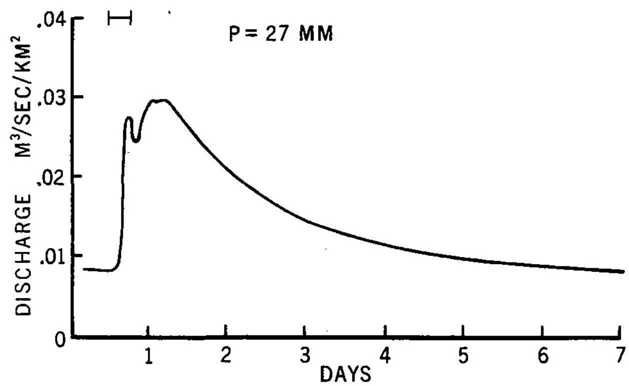

Figure 6. A stormflow hydrograph from the Whitehall Forest Experimental Watershed illustrating the delayed delivery of subsurface flow to the stream channel system following a 27-mm storm. The bar above the hydrograph represents the storm duration.

of entire basins. The soil mantle can be viewed as a zone of storage feeding baseflow and stormflow to the stream channel system. The source area for stormflow, and baseflow as well, in permeable upland basins is not a uniform or constant area, i.e., all portions of the basin are not contributing equally to streamflow. Actually combining soil water, slope energy gradients, rainfall characteristics, and basin physical parameters to predict a streamflow hydrograph is a difficult task and attempts to do so have not been successful. However, clear evidence for the predominance of subsurface movement of water in the unsaturated phase can be observed in the field under favorable meteorological conditions.

Figure 6 shows a stormflow hydrograph resulting from a brief winter rainstorm of 27 mm (1.07 inches) on the Whitehall Forest Experimental Watershed. The initial peak, which occurred during the storm, represents between 1 and 2% of the rainfall volume, actually little more than the rain that fell directly on the stream as channel precipitation. From some indeterminate area surrounding the expanding stream channel, the slowly moving subsurface water gathered to a second peak 11 hours after rainfall ceased. There is no question that this is subsurface flow; it has been verified by walking over the basin during and following storms. In addition, the maximum travel time for surface flow from the most distant part of the basin would not exceed 1 hour. As storms become larger and more complex, the hydrographs become larger and the channel precipitation peaks blend with the subsurface contributions resulting in the familiar single-peaked hydrograph. This one example from the Georgia Piedmont is not unusual. Hewlett and Nutter (1970) present evidence from several watersheds throughout the world where the second delayed peak of subsurface flow occurs as much as 4 days later.

The actual characteristics of stormflow from a watershed, really a composite of hillslope segments, depend on the pathways taken by the subsurface portions of stormflow, which in turn depend on the antecedent conditions in the soil mantle, the exact timing and intensity of the rainstorm, and the rate at which the stream channel network expands as the subsurface flow collects at the base of slopes.

A CONCEPT OF STREAMFLOW PRODUCTION

It is evident from the research conducted on hillslope segments and from field observations that the zone often referred to as the "soil moisture reservoir" has a predominant role in streamflow production from permeable upland basins. A concept has evolved over the last 10 years that accounts for soil water movement, primarily as unsaturated flow, as a fundamental process in streamflow production. This concept has been referred to as the variable, partial, and contributing source area concept (Hewlett, 1961a; Betson & Marius, 1969; Dickinson & Whiteley, 1970; Hewlett & Nutter, 1970). Although each author describes the process somewhat differently, common to all is the recognition of saturated and unsaturated subsurface flow as a source of stormflow and the nonlinear nature of stormflow production from only portions of a basin.

The hillslope segment and associated watershed research have demonstrated that long slopes can continually drain throughout the year and produce baseflow by the lateral downslope movement of water either to small zones of saturation along the stream or to the general aquifer system in proximity to the streams. Recognition of this process will help in the evaluation of soil formation and vegetation distribution and growth. For example, foresters have long recognized the improvement of site quality in headwater basins as the stream channel is approached; improved moisture relationships due to downslope migration of soil water can frequently explain the change in site quality.

Stormflow production, on the other hand, is the result of two simultaneous processes: (i) channel expansion and (ii) the subsurface delivery of water to channels. The perennial channel expands in response to subsurface flow into small draws, swampy spots, zones of low storage capacity, and intermittent channels (Gregory & Walling, 1968). The expansion is also aided by rain falling directly on these already wet areas. As the source area of subsurface flow grows, the expanding channel may grow to many times its normal width and length, often continuing to expand after the storm has ended. In essence, the stream channel system "reaches out" to tap the subsurface flow systems which can no longer transmit water beneath the surface.

The channel banks may be viewed as yielding water in a manner similar to that demonstrated theoretically by Klute, Scott, and Whisler (1965) for a saturated soil slab receiving continuous rainfall. As infiltration occurred continuously on the top half of the slab, water was flowing out of the soil surface on the lower half of the slab. Although rainfall rarely continues long enough on natural watersheds to produce saturated conditions in the surface horizons very far upslope from a channel, it is reasonable to assume that near-saturated conditions can exist at the base of a hillslope segment and that these conditions can expand upslope in a manner to suggest expansion of the channel system.

In conclusion, basin stormflow production may be viewed as a dynamic network of channels carrying off the outflow from a series of hillslope segments. The outflow source area is also a dynamic zone and for the majority of the annual stormflow represents a small area of the basin, perhaps rarely exceeding 25% of the total area in permeable upland basins. As the source area network recedes after a storm, the channel shrinks back to its original dimensions. The rate of channel expansion and shrinkage will depend on the physical characteristics of the basin, antecedent soil water conditions, and storm characteristics.

SUMMARY

The hydrologic behavior of basins is judged by characteristics of the streamflow hydrograph which represents the integration of many physical, meteorologic, and hydrologic parameters and processes. However, examination of the hydrograph alone does not reveal the sources, timing delays, or actual processes that combine to produce the hydrograph. When well-vegetated upland basins are considered to produce streamflow by a process of expanding and shrinking source areas fed by the subsurface downslope movement of water, an understanding is gained of the interaction between basin physical parameters and the flow processes which deliver water to the stream channel.

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