The Varying Source Area of Streamflow
From Upland Basins

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Introduction and Review

The variable source area concept of upland streamflow may soon become a working model to account for the various sources, pathways, and timing delays which underlie the dynamics of discharge from headwater areas. Proposed by Hewlett (1961) as a better way to interpret and explain storm and base flows from forested upland watersheds, the concept has gained some headway through various efforts of soil physicists, geographers, agricultural engineers, and forest hydrologists to apply the concept to local situations. Zaslavsky and Rogowski (1969) have recently applied similar ideas to soil formation on hillsides. Some recent models (e.g., Onstad and Jamieson, 1968) take partial account of the variable source idea, but in essence all other current models of streamflow are based on the assumption that the watershed is a lumped hydraulic system, in other words, that streamflow is generated by processes which operate uniformly over the catchment surface and therefore has a source area equal to the basin area. Often the model takes the form of a single bucket with only an overflow outlet, the "overland flow" model. At other times, several buckets are placed serially over each other with the top one delivering overland flow and one or more of the others delivering return flow (interflow, subsurface flow) and baseflow to a remote stream channel by mechanisms never made clear, although a subsurface piping system is often suggested in diagrams or flow charts. Onstad and Jamieson's model, based on a hypothesized series of cascading reservoirs up the slope from the stream channel, provides the basic outline of a model to account for a variable source area but still presupposes a linear system of reservoirs; as a consequence their model forces virtually all stormflow into overland pathways.

At this point, as always, the semantics of "overland flow" ("surface runoff") enter. Therefore, we take the liberty of defining overland flow in our own terms as rainwater that fails to infiltrate

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the soil surface at any point on its way from the basin to the gaging station, exempting only the flow of channelized water through holes along or beneath the channel system. This seemingly pedantic definition of terms is necessary to separate, in theory at least, the rapid overland delivery of water from the very slow subsurface delivery. For example, overland flow, as defined, moves at velocities up to a quarter-foot per second, more than 10,000 feet per day, whereas subsurface velocities are seldom ever in excess of ten to fifteen feet per day. Therefore, if water has infiltrated and later seeps out only a few feet downslope, it has already been delayed enough to become part of the subsurface stormflow system. Its appearance at the gaging station of a first order basin will often be sufficiently delayed to form a second peak on the hydrograph.

Forest hydrologists are well aware that overland flow (as defined) occurs rarely or in very small amounts from forests and many wildlands. In the early 1940's Hoover and Hursh (1943) drew attention to the need to account for subsurface flow in explaining storm hydrographs particularly from forested mountain land. Up to that time, subsurface stormflow had been virtually ignored in favor of Sherman's unit hydrograph and Horton's infiltration theories. During the forties, a Sub-committee on Subsurface Flow in the AGU debated the subject of subsurface flow but the debate had little effect on the hydrologic literature. Fletcher (1952) and Koessler (1950) re-emphasized Hursh's earlier ideas about subsurface flow in forests. Since then the terms "interflow" and "return flow" have been much used but never clearly defined. No way has been found to measure them on a watershed basis or apply them quantitatively to a hydrograph.

We do not plan to define such terms either. Instead we shall risk offending the ghosts of classical hydrology by questioning both the theoretical and practical value of the analysis of hydrographs by appeal to such concepts as surface runoff, interflow, return flow and the infiltration theory itself. What would a hydrologic system look like if we began with the assumption that infiltration was seldom limiting? Could we make some progress in modeling if the overland flow model was treated as a special case instead of the typical case? This idea is not so strange to hydrologists who have stood on vegetated slopes during downpours and, after watching all the water go into the ground, have later seen it pour out below into a stream channel. It also seems more believable when we consider the fact that only about 10 percent of the annual precipitation in the East appears as stormflow in headwater streams, both forested and non-forested as shown in Figure 1 from Woodruff and Hewlett (1970). Furthermore, most of this stormflow leaves the basin so many hours after rainfall has ceased that it cannot possibly be classified as simple overland flow. This follows because the distance from the perennial channel to the water divide in the East averages about 600 feet -- in other words, scarcely more than ten minutes travel time for overland flow.

In essence, the variable source area concept takes these facts into account and visualizes the response of the channel system to precipitation rates as far more crucial to the upland hydrograph than presumptive specifications about infiltration rates or "excess" rainfall.
Figure 1. Hydrologic response of the Eastern United States shown as the average percentage of precipitation that becomes direct runoff or stormflow. The weighted mean response for the area shown is about 10 percent.
over the basin. Overland flow, however defined, will be treated as an expansion of the perennial channel system into zones of low storage capacity, and thus rapid subsurface seepage into small draws, swampy spots, and intermittent channels. This expansion is aided by rain falling directly on these wetted areas. Subsurface stormflow, the bulk of the average upland flood hydrograph, will be viewed as feeding the expanding channel from below while rainfall feeds it above. In this way the channel can and does grow to many times its perennial width and length (Gregory and Walling, 1968); often it continues to grow by subsurface flow for some time after rainfall ceases, a fact we have verified by storm period observations at, among other places, the Whitehall Experimental Watershed at the University of Georgia. Others have described the same phenomenon as "quick return" flow but have too often assigned it a minor role in the flood hydrograph. A crucial feature of the variable source area system is the expanding channel network, since by this means the channel "reaches out" to tap the subsurface flow systems which, for whatever reason, have over-ridden their capacity to transmit water beneath the surface. Figure 2 shows, in a plan view of the first order basin, time-lapse diagrams illustrating the expansion of the source area during stormflow. Figure 3 attempts to illustrate the subsurface portion of the process in cross-sectional view. The rapidly expanding channel allows subsurface flow, even at velocities of only a few feet per day, to reach the channel in time to contribute to and sustain the upland storm hydrograph. It has been suggested that much of the flow from previously wetted soil zones along the channel may be displacement (translatory flow) of older water stored before the rain began (Hewlett and Hibbert 1967). As the source area network depletes, the channel shrinks back to its perennial length -- slowly, if the soil mantle is deep or slopes are long; rapidly if soils are shallow or the slopes short.

Subsurface Stormflow in Watersheds

The variable source area concept is substantially different from the traditional view of storm or flood flow as a hydrograph of surface runoff, however the latter is defined. By ignoring infiltration, which in any case has never really been connected quantitatively to the hydrograph, we allow the model freedom to accommodate the more important dynamic aspects of the runoff process, such as the inherently non-linear effect of the constantly expanding or shrinking portion of the basin that is actively involved in producing flow. The general model must accommodate both the special end-case of the universal overland flow system (the parking lot hydrograph so popular in model studies) and the opposite end-case, the excessively deep, porous basin with stable channel length and a slow delivery of stormflow almost completely from subsurface sources. Interestingly enough, published examples of both extremes exist and are available to hydrologists for study.

There is no great mystery about the one extreme, the parking lot hydrograph; the hydrology literature is replete with both theory and examples. On the other hand, Figure 4 shows one of a type seldom discussed but really not uncommon. The watershed, 130 acres in area, is located in Kenya under an annual rainfall of about 90 inches per year (Pereira, et al., 1962). It has a perennial channel deeply incised into ancient volcanic ash deposited some hundreds of feet deep over the country rock. A 2.4-inch rainfall in 24 hours produced the small channel
Figure 2. A time-lapse view of a basin showing expansion of the source area and the channel system during a storm.
Figure 3. A basin cross-section showing channel expansion and source of subsurface stormflow (after Hewlett and Hubert, 1967).
Figure 4. Selected stormflow hydrographs from Kimakia, Kenya and Wagon Wheel Gap, Colorado. The bar above each hydrograph peak represents the entire duration of the rainstorm.
precipitation hydrographs containing only about 2 percent of the rain delivered by the storm. But the bulk of the flood flow peaked four days later! Many will question the inclusion of the second peak in the flood hydrograph but in most cases it will be this peak that produces an overloading of the main valley channels downstream and therefore we should account for it as a part of the stormflow. Figure 5 shows a generalized cross-section of basins in this region of Kenya, designated Type I.

This far-off catchment is not unique. Bates and Henry's (1928) classic report on the Wagon Wheel Gap Experiment in Colorado contains similar hydrographs from a 3.14-inch rainstorm in October, 1919 -- an unusual event for that area. The basins are about 200 acres in size, average about 40 percent slope, and, as Bates and Henry pointed out, have no detectable peculiarities that would readily explain why stormflow would be detained three days on one basin and five days on the other. Obviously, these are subsurface stormflows and they constitute by far the majority of the total stormflow from the basins. Perhaps the regolith on these basins is of Type II in Figure 5.

Figure 6 shows a third example of a winter rainstorm of 1.07 inches on the 60-acre Whitehall Watershed in the Georgia Piedmont. We have made a detailed study of the subsurface features of this basin and found among other things that, typical of the Piedmont, the basin has a zone of restricted permeability at depths from 3 to 6 feet which supports and diverts subsurface flow toward the base of the slope. Basically, the basin is Type I but, because of the impeding zone, appears to behave more like Type III. Lateral flow is often seen as seep areas on the road cuts throughout this region. More flow is diverted laterally downslope in winter than in summer because of higher moisture contents in the fine-textured impeding zone. From some indeterminate area surrounding the expanding stream channel, this slowly moving subsurface stormflow gathers to a second peak 11 hours after the channel precipitation peak has occurred. There is no question that this is subsurface flow; we have "walked" it out of the basin. As rainstorms and resulting hydrographs become larger, we can see the channel contribution blend upward into the rising limb of subsurface stormflow, thus producing the familiar single-peaked "textbook" hydrograph. In summer or whenever soil mantles are relatively dry at the outset of a storm -- the single-peaked hydrograph prevails. Although partly due to increased rainfall intensities in summer, the single peak also reflects shorter subsurface pathways of delivery along the channel and the absence of any contribution from the drier surface soils upslope.

As a final example, Figure 6 also shows a hydrograph from a 1.25-inch burst of rain on Watershed 17 at the Coweeta Hydrologic Laboratory in North Carolina, a basin of deep granitic soils of exceptional permeability, most likely of Type IV. This unit storm-burst produced a rising blip containing very little water; actually just that which fell in the perennial channel and its immediate banks, and a subsurface flow peak some five hours later. In large rainstorms of lower intensity, the subsurface flow peak is much higher than the channel blip, which tends to blend into the rising limb of the hydrograph. The lack of any detectable overland flow from this basin has been reported numerous times; the senior author can personally attest to this, having walked over the basin during the final hours of a 100-year-return-period storm that delivered...
Figure 5. Schematic representation of several types of basin soil mantles.
Figure 6. Selected stormflow hydrographs from Coweeta 17, North Carolina and Whitehall, Georgia. The bar above each hydrograph peak represents the entire duration of the rainstorm.
20.3 inches of rain in five days (October, 1964). Some subsurface stormflow hydrographs on Coweeta basins have delivered as much as 6 inches of stormflow (direct runoff) in a period of two or three days.

Basins and Basin Segments

The senior author, while a member of the staff at the Coweeta Hydrologic Laboratory, began a series of watershed segment models, or soil models, to demonstrate the hydrologic importance of the unsaturated source of base flow and of subsurface stormflow (Hewlett 1961a and 1961b, Hewlett and Hibbert 1963, Hewlett and Hibbert 1967). The last of these 4 field models, not yet fully reported, was 200 feet long, 7 feet deep and 4 feet wide, running up a natural 35 percent slope. In essence, the model provided a basin segment roughly half as long as normal in the Appalachian mountain area. The watershed segment was completely isolated from the native soil by several layers of sealed plastic; an outflow pipe in a concrete headwall at the bottom collected all the discharge. A lip in the headwall at the lower end permitted measurement of overland flow, but after grass covered the soil there was no overland flow. Even the 20.3-inch storm in five days, mentioned earlier, produced no slippage and no overland flow from the structure. At no time, summer or winter, did the water table within the structure emerge from the top of the soil. Numerous raingages afforded a complete record of input to the model and a neutron meter and soil tensiometers gave a fair record of moisture and energy conditions within the soil.

Comparison of hydrographs from the model and the 38-acre watershed on which it was built are shown in Figures 7 and 8. A 4-inch September storm (Figure 7) on well-drained soils partially dried by evapotranspiration shows how responsive subsurface flow can be. The hydrograph from the 200-foot model produced an almost simultaneous peak twice as high as the basin and a duration of storm flow half again as long. Four inches of rain was sufficient to produce high moisture contents well up the slope of the model. The model segment receded rapidly under these circumstances but the watershed reveals its greater depth and length of slope by storing a larger percentage of the rain and by dropping its rate of discharge even more rapidly. Only a narrow source area along the channel yielded appreciable amounts of water to the basin hydrograph.

During an even larger storm of almost 6 inches in September, 1965, (Figure 8) the watershed yielded a substantial peak of 24 cfsm from the channel regions, but stored 94 percent of the rain and dropped rapidly back to normal flow. Obviously only a few percent of the total basin area was yielding stormflow. The model produced about the same peak flow as before (perhaps near the upper limit of the model to transmit water) but still stored 80 percent of the rain. For over 5 days the model continued to discharge stormflow at a surprisingly well-sustained rate. The outflow reflected a depleting water content and a rapidly falling water table from about 2/3 of the distance up the model (verified by tensiometer and soil moisture measurements). Ground water did not emerge from the surface of the soil at the bottom of the model. All the stormflow came from below the soil surface. Because of its shallower depth, the lower end of the model did not possess the storage to withhold 6 inches of rain for very long; however, the subsurface travel time served as a form of dynamic storage. It required a 20-inch rainstorm in
Figure 7. Comparison of stormflow hydrographs from the soil model and its companion watershed during a fall storm.
Figure 8. Comparison of stormflow hydrographs from the soil model and its companion watershed during a fall storm.
October, 1964, to force the watershed to deliver 20 percent of the rain-
fall and to behave as the model did in this 6-inch storm.

As pointed out by Eagleson (1969) in connection with the overland
flow model, "the class of watershed problems" subject to "scale modeling
is small". These watershed-model comparisons suggest one of the reasons
why this may be so. Both the depth of the regolith of the basin and the
length of the slope segment feeding the stream are variables which at
different times under rainfall tend toward independence of normally
measured features of watersheds, such as channel length, area, slope,
and so on. The comparisons also suggest that the length of a draining
basin segment can serve as a dynamic storage factor -- in a sense com-
pensating for shallow soil depths on steep slopes. Only the very excep-
tional rainstorm cancels out the advantages of the slope length, and as
a consequence overloads the soil reservoir, leading to slips, slides and
mud flows.

Note how inconsistent these subsurface flows are with the old con-
cept, so basic to the unit hydrograph method, that the time base or
duration of any storm hydrograph produced by r-units of rainfall on a
given watershed tends to be a constant. The actual time base of a
particular storm hydrograph depends on the pathways taken by the subsurface
portions of stormflow, which in turn depend upon antecedent conditions
in the soil mantle, the exact timing and intensity of the rainfall, and
the rate of expansion or shrinkage of the channel system. In addition,
the watershed as a whole has a "hysteresis loop" in its storage-discharge
relationship that is related finally to the depth of the mantle, the
length of the hillside segments, the slope gradients, and the antecedent
distribution of soil water in the hydrologically active portions of the
soil mantle. Regardless of how complex this may seem, the first order
basin is the source area for the downstream river flows that we want to
predict or control. Present models of this system don't work very well
because we have not yet succeeded in tracing, explaining, or modeling
the source areas for the hydrograph at the mouth of the first order
basin. Once we succeed in predicting the first order stream hydrograph,
current models will no doubt serve well to route the source area hydro-
graphs downstream into larger channels.

A Conceptual Model

We hope that the evidence for substantial subsurface stormflow in
the average flood hydrograph has been convincing. Whether it has or not,
it should be clear that a model watershed can be built which will operate
in the manner described. Our approach to modeling the system, therefore,
is based on the assumption that infiltration is not usually a limiting
process, that overland flow exists only to the extent implied in the
terms "over-water flow" or "channel precipitation", and that subsurface
stormflow is the dominant source of flood waters from most non-urban
watersheds. In essence there are two pathways to evaluate, channel pre-
cipitation and subsurface discharge through the wetted perimeter of
the channel and its storm period extensions. Discharge from the first order
basin may, for purposes of modeling, be reduced to a two-dimensional
sloping flow system in which two pathways are represented in a differential equation:

\[ \frac{dq}{dt} = \frac{da}{dt} \left( \frac{dp}{dt} + k \frac{dH}{dL} \right) \]

where \( q \) is the rate of discharge from the watershed, \( t \) is time, \( a \) is the area occupied by the expanding or shrinking channel system, \( p \) is rainfall, \( k \) is the saturated permeability of the stream bank and bottom materials, and \( dH/dL \) is the hydraulic gradient driving flow through the wetted perimeter into the channel. The first term in the brackets \( (dp/dt) \) accommodates channel precipitation ("over-water flow") and the second term in the brackets accounts for subsurface flow. Both terms are multiplied by the area factor \( (da/dt) \) to allow for the expanding and shrinking channel system.

In effect, the channel banks are yielding water in a fashion similar to that theoretically demonstrated by Klute, et al. (1965) on a saturated slab under continuous rainfall. They suggested that infiltration occurred continuously above the middle of the slab but that water was flowing out of the soil surface below the middle. Although rainfall rarely continues long enough to produce this end-effect on a natural watershed, it is reasonable to assume that effluent conditions can exist at the base of the watershed segment and that these conditions expand uphill in a manner to suggest expansion of the channel system. If we reduce the first order watershed to an "ideal" basin, we may represent the changing slope segment in a simplified manner as suggested in plan view in Figure 9. In effect, the lengthening of the channel shortens the segment; the reorientation of the segment is difficult to describe but may not be too important. It should be easier to deal with the variable source area concept mathematically if we assume that the entire basin can be reduced to a two-dimensional system as shown in Figure 10. Although it may do some damage to the hydrologic model from the standpoint of basin geometry, the sloping segment diagram is at least consistent as far as it goes with what we know about the behavior of water in the well-vegetated headwater basin.

We know that the mathematical expression cannot be solved as things stand. It serves mainly to illustrate the hypothesis upon which we are working. The advantage of the variable source area concept is that it represents the actual physical processes occurring on the basin. This concept should produce a more generally applicable explanation of streamflow production than the traditional overland flow model, which in itself is merely a special case of the variable source area concept.

References


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Figure 9. An "ideal" first order basin showing the location of segments during the antecedent, peak, and recession phases of the stormflow hydrograph.
Figure 10. A simple bucket model of the variable source area concept. The model assumes total infiltration except for precipitation falling on the expanding channel.


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