NON-POINT AND DIFFUSED WATER SOURCES:
A VARIABLE SOURCE AREA PROBLEM

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INTRODUCTION

Modern management techniques and new methods for detecting hazardous materials in the environment have placed new demands on hydrological science. In recent years, hydrologists have responded with a number of revised concepts for predicting and explaining the influence of water flows on these problems. Among the responses has been a revised concept of upland water flows, most frequently referred to as the variable source area concept. This concept is at the heart of the current effort to define the nature of non-point and diffuse sources of both water yield and water pollution. In order to summarize the progress made to date, we shall focus attention on the first-order perennial stream and its contributary basin.

It is commonplace to point out the great variation in drainage basins and in their hydrologic responses to precipitation. One of the sources of variation is obviously basin size. Because confusion arises when it is assumed that the hydrologic behavior of a first-order stream and the Mississippi River can be described in similar terms, it is necessary to clearly restrict the following discussion to perennial streams of small order, those headwater basins less than a square mile in area which deliver their discharges to the channels of larger streams. This system of small channels and soil mantles constitutes the domain that has given hydrologists the greatest difficulty in reducing natural complexity to an orderly set of models and techniques for use in management. As things stand, any model that could predict an accurate hydrograph from the soil mantle into the first-order stream could easily be incorporated into channel routing models that would handle downstream predictive needs. What is more important, accurate

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prediction of the headwater hydrograph implies adequate modeling of sources, flowpaths and residence time of water and solutes. Some hydrologists now feel that the variable source area concept offers the best basis for a truly predictive model of the land phase of the hydrologic cycle. While no model or concept is universal, the variable source area concept is probably more fundamental to understanding the first order stream—which is after all the source of all rivers—than any other view of the runoff process.

Because predictive hydrology took an early lead over process hydrology, and because prediction was first needed in downstream areas, most traditional concepts took little account of the exact behavior of water in the source areas of major streams. Upstream behavior was interpreted from downstream hydrologic concepts. As late as 1945, we find Horton (1945) concluding that the over-riding variable—indeed the only important variable—in stormflow and flood production was infiltration capacity under a varying rainfall or snowmelt rate. Predictive techniques and hydrologic research were dominated by this overland flow theory for many years; it was implicit in the unit hydrograph method. To this day, the number of technical papers on rainfall-runoff processes that stress restricted infiltration and overland flow run ten-to-one over papers that attempt to reopen the question of the source, pathway and turnover rates of water in the land. The trend would doubtless have continued had not the concern over "non-point source" pollutants emerged to make the mystery of the source area an important subject again.

Horton's stream order classification system serves well to delinate the domain within which various runoff concepts fit. We may define the first-order basin as that drainage basin containing the first-order perennial stream. A first-order perennial stream is unbranched during baseflows and it flows most of the time. Such a stream in the humid East has a contributing basin usually less than 100 acres, varying from 20 to perhaps several hundred acres depending on annual precipitation and soil mantle storage capacities. The basin, whether flat or steep, may comprise from a few thousand to a few million cubic yards of hydrologically-active soil and rock material that can take up, hold and release water. Eliminating from consideration at this time all arid and semi-arid lands, countless millions of such first order basins occupy the North American continent. It is within these headwaters that geological conditions and land use have their "non-point" impacts on water quality, quantity and timing. Furthermore, most of these lands can be classified as forests and wildlands, that is, non-urban and non-agricultural. The subject of this paper therefore is the land- and channel-phase runoff process in the typical first-order basin of humid regions. The restriction to humid climates is for convenience, for there is no reason to believe that the basic principles of the variable source area concept of streamflow generation does not, with modification, apply wherever water has had a dominant effect on the shape of the land.
The major influences on the shape (not the volume) of the downstream storm hydrograph lies in the channel network and its floodplain—channel steepness, storage capacity and hydraulic peculiarities in general. But the dominant influence on the volume of the first-order stream hydrograph is the porous mantle above the perennial channel. We will neglect consideration of ponds, diversions and other structures. First-order channels are generally too short and too briefly occupied by the water to exert much influence on stormflow volumes, although peak discharges and the shape of the hydrograph are affected in minor ways. As we attempt to adapt models designed for downstream prediction, and based on downstream concepts of runoff, to the headwaters, it is often overlooked that we are shifting from a channel-dominated to a land-dominated hydrograph. At this point the critical question arises, is infiltration capacity the dominant variable or not? Early observations by forest hydrologists (Fernow 1902; Zon 1927; Hursh 1944) proved to their satisfaction that infiltration capacity was not the dominant variable on forested land because rainfall rates seldom exceeded the infiltration capacity of forest soils. But runoff theory was already hardening into two schools corresponding to two problem areas: downstream flooding and abusive agriculture. For fairly obvious reasons, both these schools stressed infiltration capacity in their methodology. The observations of foresters did not develop quickly into a methodology because simplifying assumptions about infiltration could not be made.

Gradually in the 1950s forest hydrologists and others began to put together the results from a number of small hydrological experiment stations, of which the Coweeta Hydrologic Laboratory was foremost, and a general concept of an expanding and shrinking source area for storm and baseflows from forest lands emerged to replace the Hortonian concept that all floodwaters were overland flow. Figure 1 shows, somewhat simplistically, how the two concepts differed at that point.

In the Hortonian view there was an almost irrevocable classification of precipitation into stormflow (overland flow) and baseflow (groundwater recharge) at the surface of the ground. This fateful separation depended entirely on local estimates of infiltration capacity and precipitation intensities. Almost endless infiltration studies followed, finally leading to classification of nearly all soil types into arbitrary groups based on crude estimates of infiltration capacity. Whenever precipitation intensity momentarily exceeded an estimated infiltration capacity on a given soil type, the whole block was supposed to operate as a simple valve to shut off infiltration and dump water into streams. Strictly a linear-lumped system, modified only by soil type interpretations, this concept at first took little or no account of infiltration recovery between short bursts of rain, lateral subsurface movement of water during the stormflow event or the overall influence of rainstorm size. A half-inch rain that exceeded infiltration capacity was assumed to produce overland flow from virtually the same areas that would produce overland flow when a ten-inch rain exceeded infiltration capacity. Modifications, corrections and local adjustments
FIG. 1.—The variable source and Hortonian concepts of stream flow generation in the headwaters differ mainly in the major pathway assigned to storm water sources.
were added over the years but the basic model still remained a two-phased, linear-lumped concept of the runoff process. Insofar as the land-phase is concerned, nearly all current hydrograph simulation models can be classified as basically Hortonian. Such models simulate downstream hydrographs adequately but are mostly useless for source area interpretations.

First described as a relatively coherent concept in 1961 (Southeastern Forest Experiment Station, 1961) the variable source area concept treats infiltration as seldom limiting in forest and other well-vegetated land, and seldom ever the dominant variable in determining the hydrograph produced by small rainstorms (up to 1 inch in 24 hours). Instead, the hydrograph rises because of channel precipitation and grows because of the expansion of the flow system into seeps and draws that are tapping shallow or deep subsurface flow paths. A dynamic storage zone expands under the steady downslope movement of soil water. This pattern expands rapidly under intense rainfall, shrinks slowly afterward, and operates in such a way as to flush the lower slopes and shallow-soiled areas more rapidly and more frequently than the upslope and deeper-soiled areas. Infiltrated water in excess of "retention storage" is not confined to a vertical path to a water table, which in steep areas may not exist anyway. Instead water responds to changing hydraulic gradients and flows more or less parallel to the slope surface, depending on local moisture contents, soil conductivities and the steepness of gradients. Figure 2 is a diagram of a typical flow pattern averaged over all conditions; the diagram is based on an actual 200-foot sloping soil model operated under both natural and artificial rainfall. Flow paths were deduced from measurements of moisture content and hydraulic head within the model.

Disappointed in their efforts to apply unit hydrograph and overland flow models to the prediction of the hydrograph from small watersheds, a number of hydrologists in the early 60's began to modify existing models to accommodate varying source areas and subsurface stormflow. The fact that most stormflows delivered only a few percent of the causative rainfall was re-emphasized as more concern with processes in the headwaters developed. The existence of some subsurface stormflow (referred to variously as interflow, quick return flow, throughflow) was admitted, but a fundamental faith in overland flow as the prime source of the storm hydrograph lingered on. After all, it was pointed out, the movement of water in the soil and rock mantle is well-known to be too slow at best (10 to 20 feet per day) to deliver any appreciable amount of water to the channel during the stormflow event. Hursh's (1944) piping flow theory, in which animal burrows and root channels were supposed to lead subsurface stormflow quickly down the side slopes, was still offered to explain large storm hydrographs from forested basins where overland flow could not be observed in even the heaviest of rainstorms. Other hydrologists evolved the "partial area concept", which held that the small percentage of storm rainfall that became stormflow had its primary source as overland flow from a virtually fixed portion of the basin which was either impermeable or almost saturated at the beginning of the storm. Subsurface stormflow or interflow is still thought to be a minor source of stormflow in the partial area concept.
Thus we would appear to have four theories to explain source area hydrographs in forest and wildland basins. First we had the Hortonian (1945) overland flow concept, which should be fairly well relegated to cities and intensively cultivated fields by now. Second, we had Hursh's 1944 concept of piping flow, which is often noted on road cuts and stream banks as a visible phenomenon but which no one has been able to relate to the hydrograph or prove as general process accounting for stormflow. Third, the variable source area concept arose from work at Coweeta about 1960. Fourth, the partial-area concept was expounded by Betson in 1964, and has been the subject of a number of papers since. It is obvious that these are different ways of looking at the same complex process in the first-order basin, and it will come as no surprise that our thesis here is that each of the other three are merely special cases of the variable source area concept. No rigorous analysis is necessary to prove that the partial area must expand and shrink as rainstorms vary in size and intensity, nor that, where local piping systems occur, they too must operate in an expanding-shrinking mode. No rigorous demonstration is anymore needed to prove that infiltrated water is the source of most stormflows from well-vegetated forest and wildlands in humid regions. Surface water flows from impervious areas (roads, rock outcrops, cultivated or trampled fields, and saturated depressions) may or may not reach the stream as overland flow, but when it does, there seems little question that the overland source will also vary with increasing precipitation.

VARIABLE SOURCE AND NON-POINT SOURCE

If this discussion were a mere matter of whose model contains whose, it would not be worth your time at this meeting. But the practical implications of any or all of these related theories are immense in the light of our concerns with management impacts on water quality, quantity and timing. The Environmental Protection Agency is obviously having great difficulty specifying just what it means by the term "non-point source pollution," or "diffuse sources." It may seem clear enough when the term is used to distinguish between "wash-off" from urban areas and cultivated fields on the one hand, and a point-source outfall from a factory on the other. But current hydrologic models based on classic Hortonian runoff theory will, even when adjusted by coefficients, offer few valid interpretations of the source, pathway, and residence time of water, its solutes and its energy disposition within the watershed. Some of these models are being modified to include the concept of a varying source but because the concept has been tacked on, rather than built in, there remains a tendency for current simulation models to shunt more storm water into overland pathways than really occur in nature. Surface wash-off, easier to visualize than varying sources, is most often invoked to explain observed impacts of land management on stream water chemistry.

The risk of misinterpretation of non-point sources is greatest in forests and wildlands. First, the flushing or elutriation of the soil mantle will be underestimated and "wash-off" overestimated. Second,
the immediate areal source of these solutes may be assumed to be the entire basin when only the channel or its immediate environs are involved. Thirdly, turnover rates—the time required for each unit of water or solute to move through the basin—may be badly misconstrued. Fourth, erroneous mixing models will be fitted in an effort to account for the amount of new rain versus soil solution in stormflow, perhaps as a way to predict how quickly a water source will be affected by polluted rain, or how land treatment affects mineral export. If the basic core of the simulation model does not accommodate the variable source concept, but is rather made up from linear-distributed, Hortonian theory with modifications, the fitting process will most likely not reveal the physical discrepancy. Such models may predict mass outputs satisfactorily, but the hazard will lie in the interpretation of the management cause of the effect predicted.

As a simple example, let us suppose that a regulatory agency has discovered dangerous levels of a certain hydrocarbon in a stream draining a forest watershed just sprayed from the air. Per-acre applications and per-acre discharges are compared. Interpreting a simulation model based on infiltration estimates, the sudden slug of hydrocarbon is assumed to come from overland wash-off from rains following spraying. The use of the chemical is forbidden and management may be left with no alternative. But suppose further that the pilot accidentally hits a release valve while immediately over one of the headwater streams and a gallon of the material spread over an area within a dozen feet of the channel. The effect might well appear the same as wash-off from the entire basin. As a practical matter, such accidents are avoidable hazards. Management could be fined, but left an alternative to improve the control of the operation. The point is that those using the simulation model probably expect or assume that it does indeed simulate the process as well as the output. To use such models in an interpretative manner—and we will never prevent that from being the case, no matter how many cautions we include—the model must accomplish the nature of the variable source for storm and baseflows. In this case, a properly tested variable source model may have suggested the location and extent of the accident.

In another context, Kirby and Chorley (1967), and Zalavsky and Rogowski (1969), have called attention to the importance of the variable source area concept in relation to land-forming processes and soil profile development. Headward erosion by streams and the old concept of soil catenas reveals the operation of the expanding-shrinking flow of water which causes frequent flushing of lower hillslopes and colluvial-alluvial areas. Since the gravity potential and the chemical activity of water provides the energy for these processes, and since water itself is the transport mechanism for both solute and particle, it would seem obvious that a proper model of the source, pathway and energy disposition of water will be the base upon which more advanced models of geomorphological processes will be built.
NON-POINT STORMFLOWS

Another example involves the "non-point source" of stormflows and flood waters. Here we will use some recent work that illustrates the complexity of entrenched methodology based on Hortonian runoff theory. Although elaborately modified to work fairly well in predicting storm and peak flows for certain purposes, the runoff curve number method (Soil Conservation Service, 1965) assumes as a first premise that stormflows are overland flows and that every soil type within the basin delivers stormflow to the extent that instantaneous rainfall rates exceed its estimated infiltration capacity. "Antecedent soil moisture" (actually antecedent 5-day rainfall) is invoked to represent failure to infiltrate due to reduced capacity of the surface soil. A mean rainstorm storage capacity for the basin in question is assumed from averaged data from runoff plots at experimental stations. In development of the theory, no connection between actual measured infiltration rates and stormflow from first or higher order drainage basins were made. Estimated "runoff" from soil plots was added to yield stormflow from watersheds. The method has repeatedly proven intractable when applied to forest land. It tends to make no distinction between well-forested drainage basins on any other basis than average soil type and antecedent rainfall. The method offers no hint as to why two adjacent fully-forested first-order basins, classified as the same soil hydrologic group, with the same curve number, will perform entirely differently. One basin at Coweeta, for example, delivers an average of 7 times as much stormflow as its neighboring basin, although they are of similar appearance, soil type, timber type and steepness. The difference is in the soil mantle depth and distribution, which affects the variable source area of each in different ways.

Side stepping the difficulty of assessing the mantle depth on all first-order basins in the forest and wildland provinces, consideration of the implications of the variable source area concept led us quickly to a simpler and improved model for predicting stormflow. Fitted to hundreds of stormflow events on 11 forested basins from very steep to very flat land, the preliminary model takes the form:

\[ Q = 0.4 \times P^{3/2} (1 + S^{2/3}) \]  

where \( P \) is the storm rainfall in inches, \( Q \) is stormflow in inches determined by a constant hydrograph separation method, \( R \) is the average expected value of the ratio \( Q/P \) for the basin or region, and \( S \) is \( \sin(360 \times \text{Day No.}/365) + 2 \), where Day Number 0 = November 21. The latter is a simple, continuous variable that represents seasonal, and thus antecedent wetness, conditions on the basin.

The model contains no assumptions about infiltration. Rather than assigning an infiltration capacity, which the variable source concept rejects as a prime factor, we chose to assign the basin a capacity index \( R \). Preliminary maps of this index are available (Figure 3). In addition to basin capacity, the model accommodates rainfall input (\( P \)).
FIG. 3.—Average annual stormflow as a percentage of annual precipitation in most of the States east of the Mississippi. Because \( R \) in Equation 1 is computed for all rainstorms larger than one inch, \( R \) in the equation will be about twice these percentages (from Woodruff and Hewlett 1970).
and the antecedent conditions(S) that might be expected to prevail at the time the prediction is made. Although infiltration is ignored in development of the model, a direct comparison with the runoff curve method on gaged basins proved the R-index method both more accurate and more precise (Figure 4). The standard error of estimate is still rather large (0.3 inch of stormflow), but in addition to improved accuracy, this simple model has the important advantage of being easily understood. Field managers using it will not be tempted to infer anything about the areal distribution of infiltration capacities, but will be encouraged to take into account the inherent storage capacity of the basin relative to those around it. In short, the user's understanding of the runoff process will not be distorted by erroneous assumptions in the model. Better management decisions should result because there will be fewer misinterpretations of the cause and source of stormflows.

Many examples could be given that illustrate the confusion that results from the lingering faith in Hortonian theory of runoff. Our own experience includes attendance at public hearings where planners and managers are challenged to prove that various proposals will not result in overland flow, flooding, pollution, sedimentation and environmental degradation. The answers given even by the professionals are often unsatisfactory. Decisions about sewage effluent spraying, clearcutting, road building, strip mining, prescribed burning, swamp drainage, channelization, reservoir construction and aerial land treatment are affected. Impact statements contain many shaky predictions and evaluations of source area impacts because the hydrologic variable of interest is nearly always assumed to be infiltration capacity and the ease with which it is rendered critical. The attention which the Environmental Protection Agency has recently focused on "diffuse sources" specifies the problem in a nutshell: Where does streamflow and the material it carries come from? What are the pathways, the turnover rates and the source of the water and its solutes? How in general does land treatment—for example, strip mining, clearcutting or road building—affect the disposition of water energies and the resulting source of sediments? It is not too much to say that the term non-point source has no meaning aside from that given it by the variable source area concept of flows in the headwaters.

MODELING THE VARIABLE SOURCE CONCEPT

A number of hydrologists are now working to accommodate existing models for simulating streamflow to the variable source area concept and a few are attempting to model the process from the ground up. Freeze (1972, 1972a) has written a computer program for routing water through a sloping soil mass in an effort to predict the outflow as we demonstrated it earlier (Hewlett and Hibbert 1963). Freeze's model takes soil physical properties and some aspects of slope morphology into account. Although the model accommodates only part of the variable source concept (channel expansion is largely ignored), it promises to be a good base for routing water down hillslopes. Others have demonstrated various special cases of the variable source concept and
FIG. 4.--A comparison of predicted to actual stormflow (inches) by the SCS runoff curve method (triangles) and the R-index method of Equation 1 (pluses). The gaged basin is in the Piedmont of South Carolina.
have helped to bring to light specific areas of misunderstanding. We will not attempt a full bibliography and therefore apologize in advance to those whose efforts we may appear to have overlooked.

To show where the matter stands at present, we will outline the variable source model in its present form and the status of our efforts to simulate the first-order basin hydrograph on the computer. The junior author has designed a program that accommodates all major aspects of the land-phase of the source area hydrograph for the generalized first-order basin. If we may suppose a hydrograph to be simulated for any point along the perennial stream channel in the source area, there will be a contributing area that will consist of an active channel composed of flowing or standing water, seep areas wetted to the surface, and slopes of various lengths, depths and steepness. The idealized basin may be represented as in Fig. 5. Segments are described as relatively discrete subunits of the basin, each of which contributes directly to the perennial stream. A perennial stream is defined as one that flows 90 percent of the time or more, which implies that perennial channel "losses" are negligible. Segments are basically rectangular or pie-shaped in the planar view. Since without some storage provided by a mantle of porous soil and rock there would be no perennial stream, it is understood that we are not describing a bare rock watershed. Rainfall may be assumed to impinge upon these small basins in a relatively uniform manner and we can thus ignore storm movement over the basin as a factor in routing. Channel length will be a thousand feet or less and therefore channel concentration time can be assumed to be of the order of 15 minutes; the time to empty half or more of channel storage at any instant should not exceed about 10 minutes. These geometric factors suggest that a 15-minute routing interval will give sufficient sensitivity to simulate stormflow from the first-order channel. Larger streams will, of course, require channel routing programs, of which a number are in existence (e.g. Surkan, 1969).

Since we are assuming as a premise that infiltration is seldom limiting on humid region basins, what happens to the concept of overland flow? Seldom defined, and thus the source of much semantic confusion among hydrologists, overland flow was clearly intended by Horton to mean rainfall or snowmelt that fails to infiltrate because delivery rate exceeds infiltration capacity at the mineral soil surface and therefore the water travels all the way over the surface to the nearest perennial stream. It is often erroneously assumed that any surface movement of water meets this definition. Accepting Horton's definition rigorously, we hypothesize that "true" overland flow occurs only along the boundaries of the expanding or shrinking channel system, or on recognizably impervious areas contributing directly to streams. Rain water falling below that is best termed channel precipitation, since it falls on water, not soil. Water falling above the dynamic channel system infiltrates and remains within the soil, at least for some period of time.

Although there can be no finite boundary delineating the variable source area of stormflow, a critical line dividing areas of infiltration from areas of exfiltration may be hypothesized as in Figure 6. Klute, et al., (1965) apparently first called attention to this
FIG. 5.—Schematic of a first-order basin showing the conceptualization of basin segments in the variable source area model.
FIG. 6.—Schematic of the "variable source" area of stormflow and the relationship between overland flow and the zone of no filtration. For definition only—the areas shown are not intended to characterize an average field condition.
line, also referred to by Freeze (1974) as the "exit point", in an effort to model Darcy flow theory to a saturated-unsaturated sloping slab of soil. These authors concluded from simulation that such a line would assume the middle position on the slope under continuously uniform rainfall. Fortunately this seldom happens on natural slopes, for it implies a highly unstable condition that would result in mass wastage of the soil mantle because of the increased mass and pore pressure within the soil. Klute, et al., did not imply width to the zone delineating in- from exfiltration, but their model suggests that a highly dynamic irregular band of little or no filtration may exist in nature, particularly during shrinkage of the source area, upon which any further burst of rain might be viewed as delivered to mineral soil in excess of its capacity to absorb it. Under the variable source area concept this is the zone of true Hortonian overland flow, shown as an ephemeral band surrounding the expanding-shrinking channel system in Figure 6. It may be further hypothesized that the band will be narrow or absent on steep slopes with highly permeable soils, such as most of the mountain and piedmont regions of the East and the Northwest, while it may become a much more important process in flat basins with relatively impermeable soils, such as those in humid prairies and coastal flat lands. As a pertinent point, the eastern coastal flat-woods have stormflow response ratios (Figure 3) close to those of the highest and rockiest of the Appalachian Mountains. The lower mountain slopes have response ratios as low as those of the Sand Hill region of the Fall Line, where infiltration capacity is not restricting even in 10 to 12 inch rainstorms.

Figure 6 may suggest over-abstraction of the very real complexity of streamflow generation in the headwaters. Some abstraction is obviously necessary to reduce simulation to a practical tool. The rub comes in what to keep and what to throw away. Those who favor Hortonian runoff theory will obviously lean to open channel, cascade and kinematic routing of surface waters and neglect subsurface flow; those who favor partial areas will tend to neglect dynamic processes at the boundaries; those who favor piping flow will look for subterranean burrows and channels to the exclusion of Darcy-type water movement. As proponents of the variable source theory, we tend to neglect infiltration restrictions. At some future level of application, all these will prove to be fatal to the accuracy of the predictions under some conditions. The goal at this time should be to avoid those refinements in concepts that are delaying application of hydrologic models to practical management. There is bound to be disagreement among modelers as to which refinements can be neglected and still attain the goal of adequate prediction and safe interpretation of source area processes affecting pollution and other hydrological impacts.

For example, our variable source area model neglects soil water hysteresis, a tricky phenomenon of physics that is poorly understood at the soil pore level and almost impossible to simulate with accuracy in any but the simplest of porous systems. In essence, hysteresis means that the immediate behavior of a soil water "particle" is affected by the history of the medium through which it attempts to move. If the soil is wetting up, conductivity and movement are less than if the soil is draining out. As a result, we either have to ignore the effect and use averaged conductivities, or greatly expand the computer programs
and the cost required to account for it in any detail. It seems wiser at this time to neglect soil water hysteresis. But there is a macrohysteretic effect—a watershed hysteresis, if you will—that we cannot neglect if we expect any degree of reality in our simulation programs. Watershed hysteresis is implicit in the variable source area concept; the soil zones within the variable source and deep in the soil mantle will normally be draining out during rainfall, while the upper slopes and surface soils will be wetting up. Outflow rates and flow pathways will be strongly affected by basin hysteresis. This spatial phenomenon, which accounts in great part for observed differences in magnitude and duration of storm hydrographs between seasons (Tischendorf 1969), must be accommodated by any practical model of the source area.

Our approach at this time is to program a relatively crude but desirably flexible budget of the water content of any number of elements of convenient volume within discrete segments of the first-order basin (Figure 7), while allowing for the expansion and shrinkage of the drainage network with varying rainfall. Predicting water content distribution at the beginning of a storm event by methods similar to those of Helvey, et al., (1972) for the Southern Appalachians, and applying Darcy's equation for water flow to both saturated and unsaturated phases of the slope, we are passing water among I elements to simulate flow from a basin segment (Figure 8). Segment outflow, routed to the mouth of the basin, is then summed over M segments to generate the basin hydrograph. Ultimately it will be necessary to apply general routing coefficients or models for specific channel conditions to secure proper accumulation of segment outflows. However, in keeping with the discussion before, we feel that this is not the difficult part of the simulation and can be neglected for the moment.

A segment has length, depth, shape, slope and width. By smoothing local variations determined on the ground or estimated from maps, quadratic functions can be fitted to the soil surface and the bedrock surface, or any other relatively impermeable layer. The functions may also be discontinuous within certain limits; however, the complete emergence of bedrock or a road cut across a segment would require resegmentation. These functions yield estimates of element volumes and dimensions for any number of redissections of the slope during the iterative operation of the program. Another set of functions generates a mean conductivity value for each element at each iteration from known relations between moisture content and hydraulic conductivity; a budget of element soil moisture is kept for this purpose and to determine when the element becomes saturated. When any number of surface elements within the variable source area becomes saturated, the "channel surface" expands to that line and redissection of the remaining slope occurs. The program is thereby always most sensitive to the variable source perimeter.

Any number of horizons j can be introduced. Figure 8 shows only two for clarity. The I elements, here shown as I = 10, are subdivided by various rules, selected to yield smallest divisions at bottom when slopes are convex along the channel, and largest when slopes are concave; this allows the source to expand quickly over low stream banks.
FIG. 7.—Diagram of the variable source area model showing division into 10 elements \((I = 10)\) and two depths \((J = 2)\). Infiltration capacity is assumed to remain larger than rainfall rates. Shown here at the beginning of rainfall; Fig. 8 shows the expansion of the source.
FIG. 8.—Continuation of Fig. 7, showing how the variable source area model operates under storm rainfall. As surface elements \((j = 1)\) become fully saturated, storages are carried forward and the slope remaining within the zone of infiltration is redissected into 10 elements. When a surface element drains below saturation, the zone of infiltration is redissected accordingly.
and seeps as required by the early saturation of these areas. The rule for slope dissection is easily changed in the program and the ultimate sensitivity of output to this change should prove diagnostic of channel region conditions. The first $i$ elements in the top $j$ depths may be "empty" (as shown in the diagram); the empty elements become part of the stream channel as the water rises. So far the model does not accommodate inundation from segments further up the channel; we feel safe in neglecting such inundation on the first-order upland basin. It can be accommodated where necessary in a channel routing subroutine.

As rainfall continues, the stream level rises both laterally and longitudinally. Precise simulation of the areal extent of the stream and the variable source area will require basin morphological detail seldom available in either practice or research. The requirement for seemingly exhaustive physical information has always discouraged modeling of the behavior of the source area, both because research data is scarce and because such information would not be available for application anyway. However, this model is being successfully fitted to a fully instrumented 95-acre forested basin at the Timber and Watershed Laboratory of the U. S. Forest Service, Parsons, West Virginia. Hydrological and geological data are unusually complete, involving trenched soil masses, some twenty small weirs to isolate basin segments, and the fitting process is providing considerable insight into the sensitivity of the model. When the model is fitted fairly accurately to the complete first-order basin, the model itself can be used as a feedback device for interpreting hydrographs from other basins. To be worthy of this use, the program must not merely simulate the hydrograph, but its components must imitate the main processes generating that hydrograph.

To summarize briefly in symbols, we may represent the outflow from a small basin as:

$$Q(t) = \sum_{m=1}^{M} q_m(t)$$

(2)

where $Q(t)$ is basin discharge rate as a function of time in 15-minute intervals, and $q(t)$ is segment discharge rate. Channel routing coefficients are not expressed but may be added. Segment outflow may be symbolized:

$$q_m(t) = [A_1(t) \cdot K(dH/dx)] + [A_2(t) + A_3] \cdot P(t)$$

(3)
where the left term is subsurface flow (both storm and baseflow), and right term is surface stormflow and:

\[ A_1(t) \] is the water-covered area at the base of the segment, or the wetted perimeter, which changes with time.

\[ A_2(t) \] is the surface area of the stream element associated with the segment, or the horizontal projection of \( A_1 \) as it changes with time.

\[ A_3 \] represents any channel-contributing area of the segment that is pre-determined to be impervious (or nearly so) and from which all rainfall is delivered directly to streamflow. This variable is assumed zero in the normal wildland basin.

\[ K \] is saturated conductivity of the surface soils under water.

\[ \frac{dH}{dx} \] is the hydraulic gradient across the wetted perimeter or the area of the surface soil under water. It is assumed to operate at unit head in this model.

Subsurface flow through the saturated surfaces into the channel are calculated by numerical integration across the segment as follows:

\[
A_1(t) \cdot K\left(\frac{dH}{dx}\right) = \frac{1}{I} \sum_{i=1}^{I} \frac{1}{J} \sum_{j=1}^{J} d0/dt
\]  

(4)

where the symbols \( i, I, j, \) and \( J \) represent elements and depths as defined before. Soil water flow to the wetted perimeter is computed by Darcy-type equations where unsaturated hydraulic conductivity is a known function of water content within the element. This brief treatment is conceptual only but good progress is being made with the task of making it an operational model, which is the subject of the junior author's proposed dissertation.

Similar to Freeze's (1972a) computer model for a sloping soil mass, the variable source area model here described will be more flexible in application to the first-order basin. It allows easy addition of differing soil horizons (necessary to accommodate watershed hysteresis), easy variation in the shape and distribution of soil mantle segments over the slope, and easy increase in sensitivity by addition or alteration of elemental dimensions. Operation of the model is also relatively easy to visualize, a boon to those seeking a better intuitive understanding of source area processes. Preliminary runs indicate that a basin storm hydrograph can be simulated cheaply, requiring only a few seconds to a few minutes of computer time.
It is anticipated that mixing models for solute transport in and out of drainage basins can be applied to source area problems by means of a fitted variable source model. Setting aside for the moment the very difficult problems with cation exchange, diffusion phenomena and soil hysteresis, we may take a look at the mass balance of an inert solute (such as tritium) in a typical element of a slope segment. If some information on the concentration of the solute in rainfall, in the soil solution and in streamflow are available, the source and pathway of the exported solute might be interpreted from a variable source simulation fitted to a measured hyetograph and the resulting hydrograph. Much work remains to be done to apply a variable source model to routine simulation of solute movement through basins. While rainfall and discharge flush soil solutes, evapotranspiration concentrates them; therefore an evapotranspiration model that reflects the variable source area must of course be added, unless solute concentration can be predicted in advance of a rainstorm by the same technique we are using to predict antecedent soil moisture conditions. But some speculation on the form of a mass balance model is in order.

If we assume uniform distribution of an inert solute over the surface of the slope as an initial condition, it is apparent that an ensuing rainstorm of some proportions will move the solute downward into the profile and downslope toward the channel. At the end of the storm, the new distribution might appear as in the upper diagram of Fig. 9 with most of the solutes moved out of the upper horizon. However, the source of the exported solute would be the channel environs, just as with the source of the exported water. The flushing of the inert solute would thus take place from bottom to top, with the last to leave being that added at the top. If the solute had been added only at the top, as in the lower diagram of Fig. 9, the redistribution after one storm should appear as shown. Depending on rainfall amounts and evapotranspiration rates, this solute, barring decay, will be exported over a very long period of time.

In symbols, the mass balance $M$ of an inert solute in any unsaturated element $i$, depth $j$, at iteration $k$ may be written:

$$M_{i,j,k} = (C\theta)_{i,j,k}$$  \hspace{1cm} (5)

where $C\theta$ is the product water content of an element times its solute concentration $C$. This product may be computed as:
FIG. 9.—Schematic of the redistribution after rainfall of an inert solute under two patterns of surface application.
(Cθ)_{i,j,k+1} = (CP)_{i,k+1} + (Cθ)_{i,j,k} + f[(Cθ)_{i+1,j,k}] + f[(Cθ)_{i-1,j,k}] + f[(Cθ)_{i,j+1,k}] + f[(Cθ)_{i,j-1,k}]

where CP is the product gross precipitation times its solute concentration C. The functions f are computed upon element moisture content θ in the variable source model described before. Whenever the subscripts are outside the boundaries of the array, that term drops out.

Though partly speculation, these examples suggest the need for care in interpreting the cause and source of non-point pollutants and minerals from hydrological models that fail to imitate the transport processes controlling the water itself, to say nothing of ionic diffusion and exchange mechanisms within the soil mantle. In general, we might conclude that "wash-out" is more important as a transport mechanism than "wash-off," particularly in forest and wildland areas that are now receiving considerable attention from those whose job it is to regulate forest management activities under the National Environmental Protection Act. The variable source area concept and the model that eventually arises from it will provide an antidote to our historically strong dose of Hortonian runoff theory and will serve as a centralizing precept for relating management activities to stream water quality, quantity, timing and energy disposition.

The ultimate variable source model should be capable of two uses: It should be capable of predicting the hydrograph accurately when the basin geometry, the soil physical factors and the rainfall regime are known in some detail. It should also be capable of predicting the source, pathways and turnover rates of water, solutes and sediments when the rainfall and hydrograph are known with precision, but only general information about the basin is at hand. A model capable of being used for either of these purposes will provide a theoretically correct interpretation of the behavior of water in the source areas. Such an abstract understanding must precede the development of rational terminology to be used in the identification of real problems on the land. Furthermore, if we expect to develop lasting regulations for management to abide by, this abstract understanding must provide a sound basis for relating the management cause to the hydrological effect, thus to help curb the boomerang phenomenon so familiar in current regulation efforts.
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