ALTERNATIVE APPROACHES TO UNDERSTANDING RUNOFF IN SMALL WATERSHEDS

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ABSTRACT

Many recent studies have challenged the application of Hortonian type concepts of runoff production in the humid northeast and offer a more complex view of the runoff process. These non-Hortonian concepts stress the importance of partial areas, variable source areas, as well as subsurface and ground-water contributions to streamflow. A qualitative approach can be utilized to modify existing quantitative applications and to bring current practice into conformity with the more dynamic concepts which are emerging.

INTRODUCTION

Engineered plans for new developments usually include calculations of pre-development and post-development storm runoff computed by various techniques such as the Modified Soil Cover Complex (USDA, 1974), the Rational Method (Kuichling, 1889; ASCE, 1949), or a variety of other approaches (cf. Chow, 1962).

Generally such methods treat runoff as a function of rainfall intensity and the physical characteristics of the basin. Most such procedures find philosophical support in the work of Robert Horton (1933, 1939, 1945) who viewed runoff to be primarily the result of rainfall in excess of surface detention and the soil's infiltration capacity.

Horton's views were first set forth in a now classic paper (Horton,

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1933) in which the infiltration capacity of soils was proclaimed as the key physical parameter governing the formation of a storm peak. Prior to this work, runoff was calculated either as a fraction of rainfall or as being the difference between rainfall and water losses such as interception and evapotranspiration (Horton, 1933). At the time, Horton's paper was highly significant in that it provided a philosophical underpinning and a testable mechanism for determining storm runoff.

In Horton's scheme, storm runoff was the result of surface runoff plus ground-water discharge with surface runoff providing, by far, the dominant element in the formation of the storm peak. Surface runoff was viewed to be produced as rainfall rates exceed the infiltration capacity (a rate of infiltration) of the soil and after surface depressions (initial detention) were filled. Excess water then spilled downslope and coalesced as an irregular sheet of overland flow. Horton (1939) also showed that infiltration capacity declined exponentially with time through an analysis of data compiled by Neal (1938) of infiltration rates on bare soils.

It is not clear whether Horton saw overland flow as being generated over an entire basin. In his 1933 paper, Horton states that only a narrow belt along streams contributes runoff (p. 455). In his 1945 paper, however, such terms as average length of overland flow (p.284) and discussions of erosion by overland flow strongly implied that overland flow was considered to be generated over the entire basin. Common usage favors this latter interpretation for Hortonian overland runoff may be defined as:

> Direct surface runoff, generated more or less uniformly over the entire basin, and moving as overland flow across saturated soils where rainfall exceeds infiltration capacity and depression storage. (para-phrased from Kirkby, 1978, p. 2, 3, 4, 368)

More to the point, this is the concept widely employed in the development and application of most runoff calculations.

In the last two decades, many researchers have seen Horton's concepts as being more applicable to arid regions and areas of bare soil or impervious cover than to the well vegetated terrain of the northeast (except during frozen ground conditions). In this view, Hortonian overland runoff, as defined above, is seen as a special case of runoff and not the dominant process producing storm peaks in a humid environment (eg. Freeze, R.A., 1974; Dunne, T., Moore, T.R. and Taylor, C., 1975; Chorley, R.J., 1978). The more recent research sees storm peaks being produced by a variety of complex processes which collectively depart from the Hortonian view in two important ways.

1. Storm peaks are mainly the product of contributions from a fraction of the drainage basin; not necessarily from an entire watershed. This "contributing area" may vary somewhat with the seasons and with prevailing moisture conditions.

2. In most cases Hydrologic processes other than overland flow contribute the bulk of the water that produces the storm peak.

In this paper, these complex processes are collectively termed dynamic runoff.

The purpose of this work is to review some of the earlier papers, demonstrate the importance of their findings, and discuss their application to modern hydrologic practice in the northeast. The literature cited below is grouped historically and by concept according to the somewhat sequential fashion in which the various views developed. It is hoped that this compartmentalized approach to the literature will not prevent the reader from seeing the total implication of the research and the challenge it presents to the concept of Hortonian overland runoff as applied in the northeast.

PARTIAL AREA RUNOFF

Betson (1964) is generally credited with initiating the partial area concept in which a fairly small, yet consistent area of a watershed is assumed to contribute overland flow to the main drainage network. Betson used a non-linear mathematical model which incorporated Horton's (1939) infiltration capacity function to analyze the runoff from a number of basins in Tennessee. The basins were located in areas of steeply sloping terrain, ranged in size from 3.7 acres to 32.7 square miles, and included open pasture as well as more complexly vegetated areas resulting from diverse agricultural practices. The percent of area contributing runoff for the 14 basins studied was found to range from 5% to 86% with an average, less extremes, of 22%. Further verification of these results for one watershed was provided by small gaged subplots located approximately midway between the stream and the divide. Runoff from these sub-plots was usually less than 0.01 inches and was seldom recorded as occurring from all three plots during a given storm. Significantly, the basin with a contributing area of 86% represented an extreme form of land use. It was completely denuded over two-thirds of the area and was intricately dissected by a deeply incised, thoroughly integrated system of gullies. Betson concluded that in the geographic area of the study,and under normal land use practices, storm runoff frequently occurs from only a small part of the watershed area. Given this conclusion, it is clear why infiltration capacity as measured in the field versus that determined from rainfall - runoff data yielded very different values.

Ragan (1967) provided further insight into the partial area concept through a detailed analysis of a 619 foot length of second order stream segment flowing through a 114 acre forested watershed in Vermont. The watershed was underlain by 80 feet of glacially deposited sands and was monitored by 54 piezometers, 42 observation wells, an interception structure to measure subsurface flow and gages to measure the inflow from 8 seeps located along the stream. Maximum precipitation recorded was 1.32 inches with a maximum observed intensity of 6 inches/hour. For these conditions Ragan concluded that the "contributing area" for overland flow did not exceed 3% of the total watershed, and that the bulk of the water entered the channel through the seeps as ground-water inflow.

VARIABLE SOURCE RUNOFF

The variable source concept, a variant of the partial area concept, was first presented by the U.S. Forest Service (1961), the Tennessee Valley Authority (1965), Hewlett and Hibbert (1967), and further advanced by Dunne, Moore and Taylor (1975). This concept as developed by Dunne et. al., holds that runoff is generated from direct precipitation onto areas that <u>are saturated by a rising water table</u>. Runoff produced by this process has two components: (1) precipitation which, unable to penetrate the saturated soils, becomes direct runoff, and (2) subsurface water which, upon rising to the surface, is discharged to run overland to a stream. This latter component, termed return flow (Dunne & Black, 1970), provides a mechanism for the rapid discharge of subsurface water to stream channels and is observed to be sensitive to rainfall intensity.

In a detailed study of a 10 acre portion of an experimental watershed in Danville, Vermont, Dunne and Black (1970) observed the results of numerous natural and artificial (sprinkler produced) rainstorms. The 0.6 acre instrumented portion of the basin was grassed pastureland with slopes that ranged from 30% to 100%. In one storm, 1.83 inches of rain, falling within 34 minutes, followed by one half hour 2.41 inches of artificial rain to produce an event estimated to have a return period of between fifty to several hundred years (Dunne and Black, 1970). Yet, for this event no overland flow was observed on the hillslopes and measurements from the gaged subplots showed that the flood peaks were the result of variable source runoff from saturated areas along the valley bottoms.

Generally, such saturated areas are found in valley bottoms, along streams, and in swales, but various subsurface conditions can also cause saturated zones to occur in topographically high regions of a basin. The area of saturation depends on the season and expands with increases in storm size, hence the origin of the term "variable source". Dunne & Black (1970) have noted that basins generating variable source runoff respond rapidly to precipitation events and display the same type of relationship to rainfall and watershed conditions as are recognized for Hortonian overland flow. Consequently a superficial analysis might yield the false impression that Hortonian runoff was occurring in such basins.

SUBSURFACE RUNOFF

The unsaturated zone, lying above the water-table and commonly called the zone of aeration, may also supply considerable amounts of water to the storm hydrograph. Hewlett and Hibbert (1963) were among the first to call attention to the possibility that water draining from the unsaturated zone could, in certain watersheds, be the primary source of baseflow. Working at Coweeta

(North Carolina) with a 45 foot long concrete trough to produce, in effect, an inclined soil column on a 40 percent slope, the authors found that water was discharged within 1.5 days from the larger soil pores at a high rate, but continued to drain at a lower rate for the next 80 days from the entire soil mass. Moreover, the rate of discharge over time could be described by exponential decay functions which were distinct for the two phases. Subsequent studies (Hewlett and Nutter, 1970) with a 200 foot long soil model, representing a segment of a 38 acre watershed, led to the conclusion that "subsurface" flow produced the flood peak in the watershed. This conclusion also held for a 20.3 inch rainfall occurring over a 5 day period (a 100-year storm event) which produced no overland flow from the soil model or the basin. Throughout his research, Hewlett has stressed the importance of a belt of saturation, lying along stream channels, and varying in width in response to rainfall, as the critical zone from which subsurface water and groundwater emerge to form a flood peak (cf. Hewlett and Hibbert, 1967).

In forested areas of the Allegheney-Cumberland Plateau region, Whipkey (1969) determined that subsurface discharge (often called interflow) accounted for up to 60% of the stormflow for 130 separate events simulated by a sprinkler system. Interestingly, the subsurface component was the greatest in fine textured soils and appeared to be the result of flow through biological and structural openings in the soil profile.

Corbett, Sopper, and Lynch (1975) simulated rainfall on selected portions of a 19.5 acre, highly instrumented watershed, to determine the sources of storm runoff. The researchers noted virtually no surface runoff and concluded that the hydrograph peak was primarily the result of "subsurface" flow from both the upper and lower slopes with the lower slopes contributing slightly more water. Beasley (1976) used interception trenches to determined that subsurface flow from the upper slopes of a forested watershed can contribute significantly to storm hydrographs where permeable soils overlie impermeable deposits. Beasley noted that flow from the subsurface zone peaked at about the same time as channel flow and theorized that the implied rapid drainage could only occur if water traveled through macrochannels formed by decayed roots. Similar findings have been reported by Mosley (1979).

GROUND-WATER

Hursh and Brater (1941) employed a hydrograph analysis technique to determine the importance of ground-water in the formation of flood peaks on a 40 acre watershed in the Coweeta Experimental forest. They concluded that the major sources of the flood peak were from channel precipitation and discharge from the shallow ground-water zone flanking the stream channel. Yet this seemingly rapid and dynamic behavior of ground-water remained difficult for a hydrologic community, schooled in the belief that ground-water responded very slowly to rainfall, to accept.

An important advance was made by Ragan (1967, described above) who noted that wells located near the stream rose much more rapidly in response to rainfall than wells more distant from the stream, thus indicating a ground-water ridge paralleling the stream channel. Ragan theorized that where the water-table was close to the surface, a small amount of infiltrated water could convert the capillary fringe into a saturated zone to produce a rapid and local rise in the water-table. The increased gradient at the channel produced an increased rate of ground-water discharge and represented the major source of "lateral inflow" (Ragan, 1967, p. 249) to the stream.

In a more recent analysis, Winter (1983) has constructed a numerical model to study the movement of water through the unsaturated zone to the water table. His simulations indicate that recharge to the water table is variable in space and time, and that in general, ground-water mounds may be expected to develop where the water table is close to the surface and the recharging flow path through the unsaturated zone is concomitantly short. Winter's theoretical work, therefore, provides support for the observations of Ragan (1967).

Recognizing a need to separate the relative proportions of surface runoff and ground-water in storm peaks, Crouzet et. al. (1970) used tritium to index water in flood events. Since tritium in this application is largely unaffected by chemical processes, measured amounts of tritium in precipitation, ground-water and total stream discharge were used to establish relative proportions of surface runoff and ground-water discharge in storm peaks from three different basins. In two of the basins, the greater part of the flood waters were found to be the result of displaced ground-water.

More complete analyses using oxygen-18, deuterium, tritium, and specific conductance, coupled with hydrometric techniques have been applied to the study of a number of drainage basins in Canada (Sklash, Farvolden and Fritz, 1976; and Sklash and Farvolden, 1979). These studies conclude that, without exception, ground-water dominates the flood hydrograph. It may be instructive to examine more closely the findings from the Big Creek and Big Otter Creek Basins located 60 miles southwest of Toronto (Sklash, Farvolden and Fritz, 1976). These two adjacent basins cover a large area (approximately 580 mi^2) and are underlain throughout 75% of the area by a sand plain with till ridges located in the headwaters and covering the remainder of the basins. Discharge from the region was analyzed at 7 gaging stations using oxygen isotopes and conductivity to index the source of water. During the storm of May 16, 1974 approximately 1 inch of rain fell over the basin producing sharp flood peaks at all 7 stations. Prior to the storm the surficial material was nearly saturated, producing antecedent moisture conditions favoring Hortonian overland flow, yet isotopic data indicated that ground-water represented by far the largest component of stormflow (50 - 75% of the discharge at peak flow).

O'Brien (1980) used a hydrograph analysis technique to analyze discharge from two small wetland controlled (wetlands at the outlet) basins in eastern Massachusetts. He observed that ground-water levels in the wetlands rose rapidly following precipitation and in near synchronization with stream levels, indicating the importance of ground-water in forming the flood peak. During the storm of May 13, 1971 (precipitation = 1.38 inches) the flood peaks for the two basins represented respectively 0.22 and 0.24 inches of runoff above base discharge of which 62% and 53% was due to ground-water. O'Brien, hypothesized that the wetlands form an expanded and efficient ground-water discharge area, thereby accounting for the rapidity with which ground-water enters the stream.

SUMMATION

The preceeding review attempts to give only a very brief synopsis of some of the more important papers written on this subject. These papers, as well as other not cited here, provide testimony to the growing evidence that the overland flow process originally envisioned by Horton (Hortonian runoff) may not be a major factor in the production of storm peaks in a humid environment. Yet, despite these findings, such research has found little practical application to date. Indeed, as Richard J. Chorley, of the University of Cambridge, observed:

> In view of the advances in the understanding of hillslope hydrology during the past fiteen years or so, which have tended to sever many of the traditional links between overland flow and the unit hydrograph (Hewlett, Lull & Reinhart, 1968) and propagated the idea that infiltration is seldom limiting and that Hortonian overland flow is a special case of runoff (Hewlett & Nutter, 1970), it is strange that current models of basin hydrology are so little concerned with them. (Chorley, 1978, p. 31).

The goal of this paper is to indicate the importance of the current research to modern hydrologic practice in the northeast and to suggest measures by which it can be applied.

The assembled literature clearly states that Hortonian overland runoff does not dominate the flood hydrograph. Rather, storm peaks in a humid environment are produced by a complex process that apparently varies from basin to basin and may be influenced by storm characteristics. Evidence has been cited to show that storm hydrographs may be dominated by runoff from small "partial" areas or "variable source" areas, by ground-water, or by drainage from the unsaturated zone. From these diverse studies, however, two very important concepts emerge. First, storm peaks generally do not result from runoff contributions from an entire basin but from certain key areas along streams such as flanking wet areas that expand with increased rainfall. Second, the processes by which runoff occurs are different and more complex than from those initially envisioned by Horton. Current studies stress the importance of subsurface and ground-water flow and of surface runoff generated by precipitation falling on areas saturated by a rising water-table. In this paper, these processes are collectively termed dynamic runoff processes.

It should be noted that the studies report on a variety of storm sizes. Some (Dunne and Black, 1970; Hewlett and Nutter, 1970) report observations on the 100-year storm while others report on lesser storm events. For this latter group it would be interesting to learn how the various catchments would respond to the less frequent event as, for example, the 100-year flood. Yet, if the dynamic processes are dominant in the formation of the storm peak during the more frequent storm events, it seems most probable that they will continue to form a significant part of the less frequent storm peaks.

It must be emphasized that these studies do not deny the existence of Hortonian overland runoff, but see it as a special case of runoff. Indeed, whenever precipitation rates exceed the rate at which water will infiltrate into the soil, ponding must occur on the surface and can then spill downslope. It is argued, however, that overland flow is most likely to occur on unvegetated areas, where the soil has been compacted, or paved, or where the soil contains a shallow organic layer (A-horizon). Moreover, infiltration rates may vary widely over a basin and are affected by depths to soil horizons and position on slopes as well as the spatially variable infiltration capacity of the soil (Betson & Ardis, 1978). Therefore, overland flow generated on one part of a slope may infiltrate into the ground at a lower elevation and never reach a stream channel as overland flow.

DISCUSSION

There are two ways in which the emerging non-Hortonian concepts can be applied to modern hydrologic practice. First, they can be used to develop better runoff models; and, second, they can be employed conceptually in designing for runoff control.

Several models have been developed to predict peak runoff rates and volumes by using the various concepts developed in the literature. These have tended to look at floods from partial areas (cf. Engman & Rogowski, 1974; Changming & Guangte, 1980), at the movement of water through the unsaturated zone (Freeze, 1972), and at the more complex problem of the effects of spatially distributed hydraulic conductivities on hillslopes (Freeze, 1980). While these and other attempts may ultimately lead to a better, generally applicable, runoff model, it seems likely that field applications will continue to rely on the more commonly used approaches for some time to come. Indeed, if seen as a purely empirical approach to generating numbers, the existing models may adequately estimate discharge volumes and rates from specific areas. Caution in their use is indicated, however, as Hortonian based models assume a degree of homogeneity whereas the dynamic concepts emphasize spatial and temporal variability in the production of runoff. The effects of this difference might be expected to become most pronounced in small drainage areas, as opposed to larger ones, where spatial variability may be stochastically accomodated. While existing methods may be used, with caution, to estimate volumes and rates of runoff, it seems critical that the engineer in the field utilize the dynamic runoff concepts to determine probable sources of storm waters.

Knowledge of the runoff process and stormflow generation can be an important element in the design of a development site. This, in the writer's opinion, is where dynamic runoff concepts can be employed now and where lack of such consideration could be critical. The following examples are intended to illustrate this point.

Small hillside depressions and shallow wet areas with little or no peat are often considered to have minor significance with respect to the various wetland regulations and therefore worthy of little consideration. However, literature supporting the dynamic runoff concepts indicates that such areas are likely to be source areas from which runoff is produced. Therefore, runoff from roofs and roads, if channeled to these areas, might be expected to cause rapid saturation of the shallow depressions with a concomitant increase in the efficiency of runoff produced by the variable source process. Such an effect, in all likelihood, may run counter to the desired result. Further, the concept of spatially restricted runoff holds implications for the movement of chemicals from a site.

In contrast the larger, more significant, wetlands found along stream courses are widely considered to retard flood waters by serving as water storage areas. As evidence, studies such as that conducted by the

U.S. Army Corps of Engineers on the Charles River are often cited (Childs, 1970). In their study, the Corps concluded that "natural storage" (floodplain wetlands) along the Charles River was responsible for the 1955 hurricane flood peak being only 20% of the flood peak from the otherwise comparable Blackstone River Basin. However, according to the dynamic runoff viewpoint, wetlands flanking streams in "headwaters areas" may be major contributors to stormflow. According to the literature cited here these wetlands may function to augment streamflow through efficient ground-water discharge (cf. Crouzet, et. al., 1970; O'Brien, 1980) and promote runoff through the variable source mechanism (cf. Dunne, et. al., 1975). Wetlands are hydrologically complex (cf. O'Brien & Motts, 1980) such that any generalization must be somewhat tenuous. However, studies supporting the "natural storage" viewpoint versus the "major contributor" theory are not necessarily in conflict and may be explained as a phenomenon of scale.

The volume of water in the channel of the Charles River during flood is far greater than the runoff which can be produced from the wetlands along the banks. Consequently the runoff producing and conveying function of the wetlands is over-ridden and the storage capacity becomes dominant, leading to a reduction of the flood peak. Where a small tributary stream originates in a wetland, however, there is no volume of water flowing overland onto the wetland to be stored (other than direct precipitation). In this setting all runoff is generated in the wetland and the immediate environs and will flow away as rapidly as channel conditions will allow. For wetland-flanked streams that are intermediate to these extremes, the wetland function may depend on the magnitude of the flood: the runoff function being dominant for the higher frequency storms and the storage function dominating for the lower frequency storms. Such wetlands may, therefore, produce and convey runoff for the lesser rainfall events, but control runoff through storage for the greater rainfall events.

It may be concluded that characterizing wetlands located: (1) in headwaters areas as runoff producing zones; and (2) along major streams as flood storage areas, would be consistent with current research. Therefore, conducting runoff to wetlands in the expectation that their flat surfaces will store and thereby retard flood waters might not work in headwaters areas. In such cases an in-stream control structure should be used.

As another example, consider an area in which construction activities are expected to affect 5% of a given watershed. It might be argued that since only 5% of the basin is affected and that disturbing the earth will not greatly increase the runoff coefficients of the area, only a minor impact on runoff from the basin should be expected. But, bare ground and compacted earth, produced through the construction process, favors overland runoff. Therefore, according to the dynamic runoff concepts, a new runoff mechanism, not previously in existence for the unaltered condition, has been introduced. Further, floodflow is not contributed from an entire basin but from certain key areas. Should the area contributing runoff in the basin be 10% and include the development site, then the altered area represents a considerable increase to that basin and not the minor one assumed under the Hortonian viewpoint. Here, the implications of dynamic runoff are quite different from the Hortonian view.

Betson and Ardis (1978) have reported that the installation of sheet metal cut-off walls intercepted subsurface water and produced an artificial swampy area that yielded most of the runoff from a very small basin. This illustrates an important principle: subsurface flow can be blocked by walls or through the destruction of macrochannels by compaction or backfilling of trenches. The impeded subsurface flow may then rise to the surface and yield overland runoff. Indeed, Megahan (1983) has reported that subsurface flow intercepted by road cuts in logging areas, generates considerably more runoff and erosion than precipitation falling directly onto the road surface.

Finally, the writer would indicate that data is available which gives cause for consideration to the dynamic runoff view. Doehring and Smith (1978) have analyzed flood records that ranged in length from 36 to

56 years for 18 basins in eastern Massachusetts and Rhode Island. Indices for physical features as well as degree of urbanization were employed to predict flood magnitude for a given exceedance probability. Doehring and Smith found a strong correlation between degree of urbanization and flood magnitude and concluded that there was "... little doubt that dramatic increases in flood expectancy have accompanied urban growth in the study area." (op. cit., p. 53).

CONCLUSIONS

The emergence of the dynamic runoff concepts presents hydrologists with an important challenge. The research presented in this paper shows that the runoff process is more complex than previously believed; that there is considerable spatial variability in runoff potential across a watershed; and that both subsurface water and ground-water have been observed to be major contributors to flood peaks. More work needs to be done before fully quantifiable models can be applied to understanding the runoff problems of a developing area. Yet, the dynamic runoff ideas can, and should, be applied now. For the present, therefore, existing methods may be utilized to estimate discharge volumes and rates from specific areas while the dynamic runoff concepts may be utilized to determine the probable source of the waters and to guide methods of control. Hopefully, the above discussion and literature review will assist engineers and developers to consider the implications of the dynamic runoff concepts in their work.

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