SEPARATING STORM-HYDROGRAPHS FROM SMALL DRAINAGE-AREAS INTO SURFACE- AND SUBSURFACE-FLOW

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(Presented by C. R. Hursh)

Introduction—To evaluate the effects of different land-management practices on the water economy of small drainage-areas, it is essential that the stream-hydrograph obtained from small drainage-areas be separated into ground-water flow and the several components of storm-flow as accurately as the data permit. The difficulty of drawing a ground-water hydrograph for routine separation of complex storm-hydrographs has been specifically pointed out by numerous workers. For example, W. G. Hoyt [see 1 of "References" at end of paper] states that peaks occurring in such rapid succession that only rarely does surface-runoff have a chance to drain out "make the task of drawing a ground-water hydrograph difficult and the results uncertain." The improvement of present methods and the development of new methods for differentiating ground-water runoff and surface-runoff has been specifically pointed out as one of the deficiencies in hydrologic research [2].

Precipitation and other measurements essential to watershed-studies are being obtained from 30 small drainage-areas supporting continuous stream-flow and ranging in size from three square miles down to 20 acres. These drainages lie within the Coweeta Experimental Forest, an area devoted to forestry-research in the high rainfall-belt of the Southern Appalachian mountains in Macon County, western North Carolina. The mean annual precipitation of 70 inches is well distributed throughout the year. About 50 storm-hydrographs are obtained within a single year for each stream.

Description of experimental drainage-area—For the purpose of discussing some of the results of this study, records from a drainage-area of 40 acres will be used. This drainage, No. 15 on the Coweeta Experimental Forest, is a forested watershed with continuous stream-flow from pervious soils overlying a deeply weathered country rock. Discharge was measured with a right-angled V-notch weir. The lowest elevation of the area is 2,350 feet whereas the highest portion has an elevation of 3,000 feet. The water-yields from this area have been found to be quite similar to the yields of larger drainage-basins in the region.

The mean runoff expressed as cubic feet per second per square mile for this drainage for the period of April, 1936, to January, 1941, is 2.38 csm. The seasonal means are as follows: November, December, January, 2.02 csm; February, March, April, 4.10 csm; May, June, July, 2.09 csm; August, September, October, 1.61 csm.

Methods: General discussion—Analysis of a large number of storm-hydrographs calls for the use of routine practice which may be carried out with a minimum of additional replottng of the original record. It is to determine a satisfactory procedure for routine hydrograph-analysis that a special study has been made of the problems relative to ground-water separation.

As a preliminary to separating ground-water during storms, a normal depletion-curve is prepared for each drainage-area using storm recession-curves. The depletion-curve is then converted to read directly in gage-height over the weir and adjusted to the time-scale of the original field-chart. This adjusted curve is then transferred to transparent cloth and used as an overlay on the original record. Many research-problems appear in the preparation and use of curves of normal stream-depletion which will not be considered in the present discussion. It was found that for practical purposes a composite curve could be used without taking into account seasonal and annual differences. Such differences, although present, were not great enough to be significant within the mechanical errors of drafting the base-curve.

Surface storm-runoff as overland-flow has not been observed on this drainage-area; nevertheless, characteristic flood-hydrographs are produced by heavy rains. A simple hydrograph, such as Figure 1, is produced by an intense summer storm of 0.69 inches falling within a period of 30 minutes and equivalent to an intensity of 0.80 inch per hour for the entire storm. Intensities for the maximum five-minute interval amounted to 1.08 inches per hour and for the maximum ten-minute interval 1.56 inches per hour. The volume of storm-flow discharged as indicated by the rainfall above the base-line 3, Figure 1, is computed to be 1,141 cubic feet. Base-line 3 in this case is merely one of three straight lines drawn from an arbitrary point on the normal recession-curve to points (point a, Fig. 1) on the hydrograph approximately two, three, and four hours after cessation of rainfall.

Measurement of channel-area—The length of the stream-bed for the drainage is 4,008 feet and the average width is 5.2 feet. These dimensions include only the gravelly stream-bed and not the
steep heavily vegetated banks of the stream. Channel-precipitation is computed from the area of the stream-bed after making an allowance for vegetative interception, at five per cent. Using this deduction for the 0.69-inch storm producing the hydrograph shown in Figure 1, channel-precipitation is computed to be 1,198 cubic feet. As this amount is practically the same as the total discharge for the storm, it is apparent that the entire discharge above base No. 3, Figure 1, can be accounted for as channel-precipitation. Other types of storm-flow make up only a very small portion of the hydrograph.

It is believed that the importance of channel-precipitation as a component of the flood-hydrograph has not been fully appreciated. Many hydrographs similar to the one above, where practically the entire hydrograph results from channel-precipitation, have been observed on the Coweeta streams. It is possible that this factor should be more fully accounted for even in the case of much larger streams.

Storage-discharge relationship—A storage-discharge relationship may also be employed to demonstrate that the hydrograph shown in Figure 1 comes largely from channel-precipitation. If the correct separation of surface-runoff has been made by base-line 3 in Figure 1, that portion of the hydrograph above this line should be entirely the result of channel-precipitation. Therefore, the depletion of this quantity, after the end of rainfall, is simply the natural draining off of the accumulated channel-storage. Under these conditions there exists a relationship between the quantity of channel-storage (S) present at any instant and the rate of discharge (Q) occurring at that instant. This principle was utilized by Horton [3] to derive hydrographs of overland-flow from stream-flow hydrographs. The storage-discharge relationship is derived from the recession-side of the graph beyond the point of contraflexure. The procedure is as follows: Increments of discharge are added accumulatively, working from right to left, starting at the point where the separation-line meets the recession-curve (point a, Fig. 1). When any particular discharge-increment is added the accumulated quantity represents the amount of channel-storage present at the beginning of that increment. The rate of discharge occurring at that time may be related to the corresponding value of storage. A set of points derived in this manner will represent the relationship between channel-storage and discharge only if the line of separation is drawn so that very nearly all the discharge above the line is a result of channel-storage. If, for instance, the derivation of these points is carried up beyond the point of contraflexure, where the channel-storage is being augmented by channel-inflow or in this case precipitation on...
the channel, the plotted points immediately fell away from the trend of the lower points. It could be expected, therefore, that a similar distortion of the storage-discharge relationship would occur if the lines of separation were drawn in such a manner that some ground-water discharge is included in the area above the line. This was found to be the case.

Test of trial base-lines of direct runoff—Therefore, the derivation of this relationship was utilized as a test to determine the correctness of a given line of separation. The procedure is illustrated for the hydrograph of Figure 1, where three different base-lines were tried. The storage-discharge relationships derived for all three sets of lines are shown by points plotted on Figure 2. It may be seen that the points determined from base-line No. 3 plot in a consistent curve whereas the others do not. If these points are plotted logarithmically it is found that only the series derived from base-line No. 3 fall on an approximate straight line. It is concluded therefore that the third base-line provides about the correct separation.

Routing channel-precipitation—It is believed that the exactly correct line of separation would be a smooth reverse curve rather than a straight line or a series of straight lines. This point has been more completely discussed in a previous paper [4]. The results of this study serve to strengthen the belief. More recent studies of changes in the water-table of index-wells during heavy storms have indicated that a curved line more nearly represents the actual fact.

The same procedure was applied to four other hydrographs with similar results. The series of points derived from each of the five hydrographs were plotted together logarithmically and were found to produce a consistent relationship. The solid line shown in Figure 2 was derived from a straight line drawn through these five series of points. If this line represents a reasonably correct relationship between channel-storage and discharge it should be possible to route channel-precipitation through the channel and completely reproduce those hydrographs produced entirely by channel-precipitation. The hydrograph shown in Figure 1 was reproduced in this manner, utilizing the diagram of channel-precipitation shown on the Figure. The results of the reproduction are shown by the small x marks. The points are obtained by applying the storage-equation in conjunction with the storage-discharge relationship to successive time-increments.

The storage-equation in its fundamental form is as follows:

\[ S_1 + P_{ch} - Q = S_2 \]

where \( S_1 \) = channel-storage at the beginning of a time-interval, \( S_2 \) = channel-storage at the end.
of a time-interval, \( P_{ch} = \) increment of channel-precipitation during interval, and \( Q = \) average rate of outflow during interval.

If a sufficiently short time-interval is selected it may be assumed that \( Q = \frac{Q_1 + Q_2}{2} \), where \( Q_1 \) and \( Q_2 \) are the rates of discharge at the beginning and end, respectively, of a time-interval. The equation may then be rearranged into the following form:

\[
(S_1 - Q/2) + P_{ch} = (S_2 + Q/2)
\]

The use of the storage-equation in this form to permit a graphical solution was first brought to the writers' attention by C. O. Wisler, Professor of Hydraulic Engineering, University of Michigan.

Graphic solution for routing channel-precipitation—In this form the solution may be accomplished graphically by utilizing the auxiliary curves shown in Figure 2. Knowing the rate of discharge of the beginning of any interval, the amount of \( P_{ch} \) occurring during that interval is added to the particular abscissa of the \((S - Q/2)\)-curve which corresponds to that discharge. The abscissa equal to \((S - Q/2 + P_{ch})\) is thus obtained. Vertically above or below this point will be found a point on the \((S + Q/2)\)-curve which indicates the rate of discharge at the end of the interval. This procedure may be quickly carried through for successive intervals. The length of interval was taken as five minutes in this case. It is obvious that care must be taken to keep all the elements of the storage-equation in the same units. It will be noted that the points obtained, Figure 1, give a fairly good reproduction, even for the rising side of the hydrograph. This would seem to be a further indication that the storage-discharge relationship is the correct one and that the graph in this case is chiefly the result of channel-precipitation.

Tests for subsurface storm-flow—It would make little practical difference whether base-line 1, 2, or 3 were selected in the hydrograph of Figure 1, since the amount of discharge above the base-line would not vary by a significant amount considering the accuracy of hydrologic observations. However, the chief purpose of studying such simple graphs is the derivation of information which may aid in the solution of more complex cases. Such a case is the hydrograph shown in Figure 3 resulting from a continuous long rain. The hydrographs shown in both Figures 3 and 1 are midsummer storms. The rainfall-intensities that produced the hydrograph on Figure 3 are not nearly so intense as those producing the hydrograph in Figure 1. Since it has been demon-
strated that no direct overland storm-flow occurred in the storm of Figure 1, it would follow that precipitation-intensity could not have been great enough to exceed infiltration-rates for the storm of Figure 3. Consequently, on this basis of reasoning, no part of the hydrograph in Figure 3 could have resulted from direct runoff other than channel-precipitation. Evidence to substantiate this belief is obtained by using still other criteria to facilitate the separation of the storm-hydrograph. One of these is the use of the unit-hydrograph or distribution-graph. Another is the use of depletion-ratios. Still another is the observation of changes in the water-table of index-wells.

The hydrograph in Figure 3 is unlike the hydrograph in Figure 1 in that channel-precipitation accounts for only a minor portion of the total flow. This was shown by routing the channel-precipitation through as was done in Figure 1. In this case the points are plotted downward from the actual hydrograph with the intention of establishing the approximate location of the base-line. The time-element involved in locating these points may be somewhat in error. That is, the location of the group of points as a whole could reasonably be shifted to right or left through an increment of a few minutes. However, the quantity of water represented by the area above the points accounts for all the channel-precipitation while all that below the points appears to have resulted from underground storm-flow or ground-water flow.

Use of the unit-hydrograph—The approximate correctness of the line of separation of channel-precipitation in Figure 3 is further substantiated by the use of the unit-hydrograph or distribution-graph. The base-length of the distribution-graph for this drainage-area is about two hours and ten minutes. Effective rainfall ends at about 2:50 P.M. Therefore, according to the distribution-graph, all channel-storage derived from channel-precipitation must have passed the gaging-station by about 5 P.M. This agrees approximately with the results as obtained by routing channel-precipitation.

Use of depletion-ratios—When the discharge depletion-ratios of the recession-side of the hydrograph in Figure 3 are determined by half-hour periods, it is found that at no point is the ratio less than 0.92. (This ratio is obtained by dividing the rate of discharge at any instant by the rate occurring one-half hour earlier. Any other interval could be chosen.) The value for the ordinary dry-weather depletion-curve of discharge for this stream is about 0.9996. For several days following a rain the depletion-ratio varies from 0.92 to 0.99. Depletion-rates for direct runoff known to be of surface-origin are 0.88 or less. In no other part of the several years of records obtained on this stream does the ratio become less than 0.92. The fact that at no point on the recession-curve shown in Figure 3 is the depletion-ratio less than 0.92 may be considered as further evidence that the discharge shown in the hydrograph below the base of channel-precipitation is made up of underground storm-flow.

The ground-water hydrograph—Underground storm-flow has been commented on by numerous writers. It has been referred to in a previous paper [5] as storm-seepage and subsurface storm-flow. Barnes [6] in a discussion of the structure of discharge-recession curves makes use of depletion-ratios and considers that the storm-discharge of streams in the upper Mississippi Valley is made up of the two components, surface-flow and storm-seepage. He has indicated a process by which these two components can be separated by graphical analysis.

Melnzer [7] has repeatedly called attention to the importance of continuous water-level records for interpreting ground-water phenomena. For small drainage-area studies well-records have proven to be invaluable.

In a previous discussion by Hertzler [8] on storm-hydrograph analysis for drainage-areas on the Coweeta Forest, it was assumed that the rise of the ground-water base starts at the beginning of stream-rise. This was based on observations of a limited number of wells. Recent studies of the water-levels of wells actually within the small drainages from which the hydrographs are obtained now indicate that there may be a delay of several hours before a significant rise of ground-water occurs.

So far as storm-water may actually become part of an established water-table, it may also be considered as storm-augmented ground-water. The rapid percolation from this water could then be called augmented ground-water discharge during storm-periods. It is differentiated from recognized ground-water discharge only by its faster percolation-rates or by the time of its reappearance in the stream-channel.

Obviously the underground storm-flow contributing to the lower portion of the recession-side of the storm-hydrograph has more nearly the characteristics of true ground-water, whereas that contributing to the upper portion has more nearly the characteristics of channel-interception.
Use of well-records—Well-records also give an indication as to the nature of the water making up the major portion of the hydrograph shown in Figure 3. Changes in the height of the water-level of two Coweeta Forest wells, but not situated on the drainage-area No. 13, are shown in the same time-scale on the storm-hydrograph. It is apparent that there are different types of rises shown by the two wells. By a study of previous storms Well A-4 is known to rise slowly and to fall slowly and to tend to follow the seasonal depletion-curve of the stream-hydrograph. At the end of the time-period shown in Figure 3, it is still rising and will eventually meet the curve of normal stream-depletion. Such a well appears to be more closely associated with normal stream depletion than with the storm-hydrograph. Well B-3 tends to follow the storm-hydrograph much more closely. The shape of the other well-hydrographs for this storm ranges from low rises similar to Well A-4 to even more rapid rises than Well B-3 but similar to it. Apparently, the hydrograph below the separation-line of channel-precipitation is built up from storm-water temporarily stored along water-tables in close enough proximity to the stream to contribute a significant amount of percolated water during the period of the storm. Whether or not a portion of this water should be called ground-water discharge is apparently a question of definition.

What has been most lacking is an explanation of the nature of underground storm-flow and some proof that it can be related to measurable ground-water phenomena. An explanation has been sought in the changes of water-levels of selected wells. These wells are selected with regard to topography, soil-profile, and proximity to the stream.

Wells to be used for indicators of this separation must have been studied for a sufficient length of time to standardize their performance against the stream. For example, those wells known to fluctuate in keeping with seasonal depletion of the stream are probably the ones that indicate significant water-rises of seasonal ground-water stores. Such a well is indicated by A-4 in Figure 3. Those wells that rise rapidly and produce hydrographs similar to Well B-3 in Figure 3 are the ones that indicate the position of important water-tables contributing to subsurface storm-flow during the storm-period. Consequently, with a previously determined knowledge of the behavior of a particular well in relation to the stream-hydrograph, it is possible to use the well-hydrograph for the separation of storm-augmented ground-water flow.

A possible explanation of the behavior of different wells lies in their relative position with regard to topography and proximity to the surface-stream. The Well J-1, Figure 4, has a water-level ranging from six to nine feet below the ground-surface. It is on drainage-area No.
In the storm shown in Figure 4, and in numerous other storms that have been studied, there appears to be a time coincidence between the maximum height of the water-level in Well J-1 and the sharp break in the depletion-ratios on the recession-side of the hydrograph. This break is believed to be the significant reference-point for drawing in the ground-water hydrograph. At this point, the forms of storm-water most nearly approaching channel-precipitation have passed the gaging-station. The recession-hydrograph shows depletion-ratios in the magnitude of normal ground-water depletion. It is reasonable to believe that the stream is now receiving normal ground-water from higher water-table levels resulting from the storm. The general shape of the hydrograph of Well J-1 suggests that the falling of the water-level of the well tends to follow the shape of the recession of stream-discharges. The fact that the water-level of the Well J-1 falls rapidly indicates that ground-water percolation from certain portions of the drainage-area may be reaching the stream at a relatively rapid rate during the storm-hydrograph.

Hydraulic significance of rise in the water-table—It is recognized that many types of ground-water may contribute to storm-flow. One rough classification of these types might distinguish between that water which actually reaches the water-table and that which does not. The hydrograph shown in Figure 3 is largely of the former type. The cause of this sudden increase in ground-water (gravity-water) discharge may be explained by considering the hydraulics of percolation along with the evidence of changes in the elevation of the water-table as shown by well-records. Two of the more important variables which might affect the discharge are the cross-sectional area through which the water may enter the stream and the slope of the water-table at the stream-edge. Since these steep mountain streams tend to rise very little during a storm, the change in cross-sectional area is not a major factor. However, it is possible that the slope of the water-table at the stream-edge may increase considerably during the storm-period. If, for instance, the slope changed from one in 20 to one in five during the storm, the discharge would be four times as great if flow is laminar or twice as great if flow is turbulent. The evidence indicates that a much greater change than this might occur at the stream-edge where during a long rain the water-table may actually follow the ground-surface for a short distance on each side of the stream. It should be emphasized that it is the slope directly at the water's edge which controls the contribution to the stream. It is quite possible that at some distance from the stream the water-table might temporarily slope away from the stream, but this would have no immediate effect on the rate at which ground-water enters the stream.

Applications and conclusions—For routine practice the sharp break of the recession-hydrograph is used as a reference for a new maximum on the normal depletion-curve extended under the hydrograph from the right. As a rule the location of this break may be quickly found by plotting a few recession-ratios of discharge above normal depletion by half-hour intervals. The actual ratios are not so essential but the trend of the plotted points is an aid to the eye in locating a major break in the recession-curve. In practice this is done quickly on the original chart and kept as a permanent record.

This plotting procedure alone may be used to locate the point of rise of ground-water to a new discharge-level for simple storms without reference to the well-hydrograph. For compound storms where there is a masking of the recession for any precipitation-period by a second rise, the index-well peak can be substituted for the plotted depletion-ratios. In any case the index-well peak may be used as a check on the location of the point in question should it be difficult to locate by other methods. On some storm-hydrographs this point may be located through inspection for practical purposes without further check.

The point A in Figure 4 is located on the normal depletion-curve from the left a time-distance indicated by the beginning of the rise in the water-level of Well J-1, or any other similar well having a storm-peak that coincides with the maximum break on the storm-recession hydrograph. Three lines might then reasonably be drawn for the base of the ground-water hydrograph, A-B, A-C, and A-D.
For the Drainage-Area No. 13 on the Coweeta Forest, it would be logical to draw in the base of ground-water to appear quite similar to the shape of the hydrograph of Well J-1. In practice a straight line is actually used on the head chart because this can be drawn more easily than a curved line. The difference between the curved line and the straight line in reading the head chart would not be important. This base for ground-water is shown as line A-D, Figure 4. The discharge below this base may be viewed as storm-water that has reached the stream as storm-augmented percolation of gravity-water. The discharge between this base and the base of channel-precipitation may be viewed as rapid seepage through unsaturated soil-profiles, or as coming from naturally wet areas closely associated to the surface-stream.

By applying such procedures as have been discussed it is believed to be possible to obtain a greater degree of uniformity in the routine separation of subsurface-flow in storm-hydrographs than could be obtained by inspection alone.

A complete explanation of storm-seepage on the drainage-area under discussion must await further studies of water-tables under additional conditions of soil-topography. In the light of the present information on the subject, the storm-hydrograph such as is shown in Figure 4 from Drainage-Area No. 13, appears to be made up of storm-water from the following sources, arranged approximately in the order in which they may contribute to the storm hydrograph:

1. Channel-precipitation.
2. Contributions from areas of normally shallow water-tables located in close proximity to the stream, and occurring in soil-profiles which are quickly saturated. Where such conditions occur along a stream, it is expected that there will be an actual increase in the width of the channel and subsequent increase in the amount of channel-precipitation. Areas of high water-tables adjacent to spring-heads would be expected to contribute similarly.
3. Storm-water moving through layers of porous soil-material close to the surface and under considerable gradient and reaching the stream during the period of the storm-hydrograph. Frequently, such layers overlie those that are much less porous, as for example, is the case between A- and B-horizons of many soil-profiles.
4. Storm-seepage from large bodies of colluvial or other porous soil-material that has filled in along stream-banks. Storm-seepage along natural subterranean drainage-lines that exist in filled ravines and valleys.
5. Storm-seepage as a result of actually piling up of a high water-table in talus-slopes in close feeding relation to the surface-stream. These talus-slopes are fed by relatively rapid seepage or percolation from steep slopes. The depletion of this temporarily stored storm-water in relatively porous material may account for the recession-side of the hydrograph until its approach to normal depletion-rates.

It is conceivable that all the forms of storm-water mentioned above may contribute to the hydrograph in some orderly fashion related to time. On drainages of uniform topography and soil-mantle this time-factor may become a valuable tool for the study of storm-water. On less uniform drainage-areas any regular appearance of the different types of storm-water into the stream will be more difficult to observe.

References


W. G. HOYT (U. S. Geological Survey, Washington, D. C.)—It is with considerable pleasure that I discuss the paper by Hursh and Brater entitled "separating storm-hydrographs from small drainage-areas into surface- and subsurface-flow". The paper marks a distinct advance in our knowledge of what we may call the stream-flow cycle in drainage-basins of significant size in contrast or as a complementary part of the surface- or overland-flow cycle. By this I do not
mean that we still do not have a long way to go. The authors have, however, presented some
definite factual information concerning the magnitude of subsurface storm-flow. With respect to
the surface-runoff phenomena we are deeply indebted to many who, based on the large amount of
data collected at experimental areas during recent years, have developed sound, rational con-
cepts of surface runoff as such. Others have developed rational theories and concepts relating
more specifically to the movement of water after it has reached river-channels. Still others
have struggled with the complexities involved in what is so apparent, namely, the rapid transi-
tion of rainfall into flood-flows in areas where apparently there is little, if any, surface-
or overland-runoff. It is this phenomenon which Messrs. Hursh and Brater have so clearly des-
cribed in so far as certain areas in the Coweeta Experimental Forest are concerned. They give
quantitative expression to a phenomenon that many have felt for some time has a distinct bearing
on flood-flows as such. In general, I believe up to within a relatively few years ago hydrolo-
gists looked upon water in the ground mostly with respect to a more or less static water-table,
its rise and fall. Hydrograph-analyses such as made by Messrs. Hursh and Brater in conjunction
with the results of experimental data indicate that there is a dynamic phase of ground-water
flow associated with floods. This dynamic phase is of considerable significance in present
problems and is a phenomenon about which we have much to learn. It is in the study of this
phenomenon that students of ground-water can be especially helpful.

The facts presented by Messrs. Hursh and Brater seem to indicate, to me at least, the possi-
bility, as Mr. Snyder pointed out in 1939, and also as discussed at the round-table held last
year, that it may be necessary when considering stream-flow as such to consider the division of
rainfall into surface-runoff and ground-water runoff to take place both on and below the soil-
surface instead of entirely above the surface. In other words, in so far as direct flood-runoff
in contrast to surface-runoff is concerned, may not many of our phenomena relating to surface-
detention, net rainfall-excess, and infiltration relate not only to the surface of the ground but
to an indeterminate zone lying at and extending a considerable distance below the ground-surface?
In developing such a concept I do not believe we would be in any way retrogressing in our think-
ing but rather believe we would be taking a step forward with respect to our knowledge of stream-
flow from drainage-basins of significant size.