AN EXPERIMENTAL INVESTIGATION OF PARTIAL AREA CONTRIBUTIONS

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ABSTRACT

The paper describes a detailed experimental-numerical investigation of the concept of partial area contributions to storm hydrographs. A computer solution of a numerical flood routing technique was used to isolate the time-spatial distribution of local runoff entering the main channel of a small watershed. Extensive experimental information collected in the vicinity of the 619 foot length of second order stream provided a means of interpreting these land-phase hydrographs.

Analysis of a series of storms showed that only a small portion of the watershed ever contributed flow to the storm hydrograph. The contributing area was found to be a function of the storm duration and intensity and, rather than being uniformly distributed along the length of the channel, it existed in the form of localized zones of intense contribution. In a given storm the contributing area was found to fluctuate with changes in the rainfall intensity. During periods of low intensity, most of the flow came from channel precipitation and rain falling an the wet areas surrounding a series of seeps. If a period of high intensity occurred, flow developed through the forest litter on the hillsides and thereby created a larger contributing area. No interflow in the soil mass above the water table was encountered. A rapid response of the ground water at some points along the channel, however, might have been interpreted as interflow if extensive measurements had not been taken.

The behavior of the watershed was quite logical when the fundamentals of the individual processes were considered. The results of the study illustrate that there is a need for a re-eveluation of some of the traditional methods used for runoff computations. Further, any parametric model developed for the synthesis of hydrologic events should be able to reflect partial area contributions.

RÉSUMÉ

L'objet de ce travail est une étude numérique et expérimentale détaillée de la conception selon laquelle une partie seulement du bassin contribue aux crues causées par les averses. Les solutions que donne une ordinateur quant à la prévision des inondations ont été utilisées pour isoler les distributions temporelle et spatiale de l'écoulement local pénétrant dans le lit principal d'un bassin hydrographique. Les renseignements expérimentaux considérables ramassés au voisinage des 650 pieds d'un cours d'eau secondaire ont permis d'interpréter ces phénomènes d'infiltration.

L'analyse d'une série d'averses a montré que seule une petite partie du bassin hydrographique ne contribuait jamais aux crues d'averses. On a trouvé que l'étendue de la zone en question était fonction de la durée et de l'intensité de l'averse et plutôt que d'être distribuée uniformément le long du lit, elle existait sous la forme de zones localisées à contribution intense. Pendant une averse donnée, on a trouvé que la zone de contribution fluctuait selon le changement d'intensité de la chute de pluie. Pendant les périodes de faible intensité, la majeure partie de la crue venait des chutes de pluie, sur le lit même et sur la zone détrempée qui entoure un réseau de sources. Si une période de forte intensité se produisait, l'écoulement se faisait à travers les taillis des versants des collines créant ainsi une zone de contribution plus importante. Aucune intercommunication des eaux n'a été trouvée dans le sol au-dessus du niveau supérieur des eaux souterraines. Une réaction rapide des eaux souterraines en quelques endroits le long du lit, aurait pu, néanmoins, être interprétée comme une intercommunication si des mesures excessivement précises n'avaient été prises.

Le comportement du bassin hydrographique était assez logique si l'on considère les principes des phénomènes individuels. Les résultats de l'étude illustrent le besoin qu'il y a de re-évaluer quelques-unes des méthodes traditionnelles employées pour l'estimation des crues. De plus, n'importe quel type de paramètre utilisé menant à une synthèse des phénomènes hydrologiques devrait pouvoir refléter ce facteur de la contribution partielle.

Introduction

Many hydrologists believe that only a portion of the watershed area contributes runoff to the storm hydrograph. The findings of a number of recent watershed studies have provided increased justification for this belief. Several of these studies have been directed by staff members of the Tennessee Valley Authority. Betson (1) examined the concept of watershed runoff through the use of a series of mathematical models based on the integral of an infiltration capacity function. Using data from two small watersheds and testing his hypotheses through multiple correlation analysis, he concluded that contributions to storm hydrographs originated from a small, but relatively consistent, part of the watershed. An examination of the behavior of two watersheds in the Elk River Basin of Tennessee (2) led to the conclusion that the watershed was a dynamic one and could vary in size as a storm progressed. It was believed that most of the flow came from the valley floors where the soil moisture was high. Hewlett and Hibbert (3), considering a forested watershed, proposed a dynamic model that derived its storm flow from valley areas near the stream and a variable source area located on the lower slopes of the hillsides. Amerman (4) was led to the conclusion that partial area contributions were significant in a study conducted on an agricultural research watershed in Ohio. He found that the runoff producing areas could be distributed in a seemingly random fashion on ridge tops, in valley floors, and on valley slopes. Zavodchikov (5) considered the role of partial area contributions in his definition of an "effective area". He considered runoff production to be controlled by an effective area which was a function of the general topography of the watershed and the soil moisture.

The present study was undertaken to gain additional insight into the details of partial area contributions. An experimental-numerical procedure was concerned with the identification of the major components of flow entering a natural channel during a period of runoff. The object was to isolate the components of flow and to determine their magnitude, time-sequence of arrival, and their origin. The results clearly show the significance of partial area contributions in the production of runoff in one watershed. Further, the information obtained provides an opportunity to assign a physical interpretation to flows coming from several sources that were located by either experimental measurement or computation.

Approach

Site selection and mathematical model

When undertaking any field investigation, the research hydrologist must have a mathematical model that has sufficient logic to properly define the quantities with which he is concerned and it must have sufficient flexibility to be applied in nature. Further, if a meaningful physical interpretation is to be derived from his results, the site chosen for investigation must have sufficient uniformity to allow the limited experimental data that it is possible to collet to be meaningful and representative of the dominant processes.

Flow in the channel system of a watershed during a period of runoff is unsteady and spatially varied as a result of local runoff entering along the length of the stream. Stoker (6) has shown that a mathematical description of this flow system requires the solution of the differential form of the continuity and momentum equations given as

$$\frac{\partial A}{\partial t} + \frac{\partial (AV)}{\partial x} = q \tag{1}$$

and

$$V\frac{\partial V}{\partial x}+g\frac{\partial y}{\partial x}+\frac{Vq}{A}+\frac{\partial V}{\partial t}=g(S_0-S_e) \tag{2}$$

where the terms have their usual meaning. Many investigators have used numerical solutions of these equations for flood routing and other problems of unsteady flow. The author (7) has shown that a numerical solution can be used to synthesize the time and spatial distribution of lateral inflows entering a channel. To be used to synthesize inflows to the channel, however, the numerical solution of equations (1) and (2) requires the precise definition of such quanities as the local channel slope, roughness, cross sections, and the initial distribution of inflows. Because of these difficulties, it was decided not to attempt to apply the complete equations to the problem of a stream draining an upland watershed. Rather, it was decided to use a model based only on equation (1) where most of the components would be determined experimentally.

After an extensive survey of watersheds in the region, the area selected for this study was a 619 ft. length of second order stream draining a 114 acre portion of a forested watershed near Essex Center, Vermont. The stream was selected because of the relative uniformity of its channel geometry and the lack of major complications in the geomorphology of the surrounding watershed. The watershed had formed as a series of deltas deposited during the step-wise recession of a post-glacial lake. As a result, the topography of the watershed could be broken into two relatively uniform soils consisting of approximately 80 ft. of uniform sand deposited on a horizontal layer of gray silt of unknown depth. This minimized the difficulty of non-homogeneous soil groups and geologic structures, and the sandy nature of the soil allowed easy intallation of all experimental equipment. The drainage network had eroded through the sand to the more dense gray silt. This led to the formation of an extensive and well defined ground water table.

A detailed survey of the channel led to the model shown schematically by figure 1. Q_U represents the flow entering the channel over an upstream control structure, and Q_D represents the flow leaving the channel over a downstream control structure. The other quantities represent the local inflows that could be identified. Q_P is the channel precipitation determined from the length and width of the reach and Q_B is the baseflow entering the reach before the storm. Q_W represents the flow coming from a series of small wet areas and entering the channel at eight points along its length-hereafter refered to as seeps. The remaining term, Q_L, represents the other components of runoff This latter term could not be measured directly and it was recognized that it could include overland flow, interflow and ground water flow. The concepts represented by figure 1 allowed equation 1 to be written as

$$[Q_B+Q_U+Q_P+Q_W+Q_L]-Q_D=\Delta S/\Delta t \tag{3}$$

where $\Delta S/\Delta t$ represents the change in channel storage during the time period Δt. Since Q_L was the only component of inflow that could not otherwise be identified, it was determined on an IBM 1130 digital computer be rearranging equation 3 as

$$Q_L=Q_D-Q_U-Q_P-Q_W-Q_B+\frac{\Delta S}{\Delta t} \tag{4}$$

In this context, Q_L is the average ungaged lateral inflow entering the channel during the time period Δt. The origin and significance of Q_L was to be determined through extensive land-phase intrumentation. Other quantities in equation 4 were to be determined from channel-phase instrumentation.

Channel-phase instrumentation

Extensive instrumentation in the channel was necessary to determine the quantities necessary for the solution of equation (4). The upstream and downstream discharges were measured by 90° V-notch weirs equipped with continuous water level recorders.

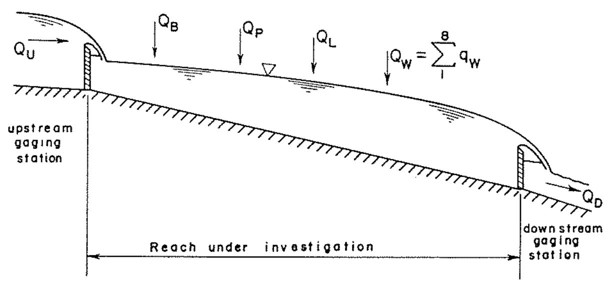


Fig. 1 — Schematic of inflow elements.

Inflows from the eight seeps along one side of the stream were obtained by installing galvanized iron V-notch weirs at their points of discharge. Three of these weirs were equipped with continuous water stage recorders. The remaining seeps were equipped with crest gages. A relationship between the recording weirs and the individual non-recording weirs was obtained by making continuous measurements during a series of storms. In the use of any routing technique based on the continuity equation, one of the most difficult parameters to estimate is the term $\Delta S/\Delta t$, or the rate of change of storage. Often, this accomplished through the use of coefficients determined from past records which relate the storage of the channel to either the downstream depth or a weighted average of the upstream and downstream depths. Such a step leads to considerable uncertainty. An examination of the channel profile revealed that it could be broken into four reaches having relatively uniform slopes. Eighteen stations were established at which cross sectional areas were obtained. These sections were not distributed uniformly along the length of the channel, rather, they were chosen to reflect significant changes in the cross section and to provide reasonable coverage of the four segments of the channel. These stations were mapped during the steady state conditions and, through the use of a portable tape recorder, during the actual passage of hydrographs. With this information the changes caused by bed movement could be incorporated into the program. Depth determinations made during storms showed that the behavior of the stations near the lower end of the channel could be monitored by the recorder on the downstream weir. Similarly, the four stations near the upper end of the channel were related to the depths measured at the upper weir. The depths at stations in the two intermediate reaches were reflected by two water level recorders placed at the section mid-points. As a result, it was possible to determine the rate of change in storage in the channel during the passage of the flood through the use of the four water level recorders and the related cross-sections at eighteen points.

Land phase instrumentation

Gross rainfall was measured through the use of one recording gage and one USWB 8-inch standard gage located in open areas. A relationship to estimate the quantity of rainfall intercepted by the trees was developed through the use of 20 ground level gages under the canopy..

If a meaningful physical interpretation was to be given the computed Q_L, measurements reflecting changes in the soil moisture and ground water had to be obtained. In addition, some technique to evaluate the significance of overland flow and interflow had to be devised. Four nuclear access tubes were used to estimate changes in the soil moisture storage. This was accomplished through the use of a nuclear probe by taking readings before storms, during, and for several days following a period of rainfall. These stations were located in the immediate vicinity of the stream, further out in the floodplain, and on the hillsides.

A portable siesmograph was used to determine the location and general configuration of the ground water table. This was quite successful since the soil was relatively homogeneous and no geologic obstructions existed. Ground water variations in the vicinity of the stream were monitored through the use of fifty-four piezometers and eighteen observation wells arranged in two lines perpendicular to the channel. Twenty-four additional wells were arranged in interlocking triangles to detect changes in direction. During a storm, water levels in those observation wells not equipped with recorders were measured as often as possible through the use of an electric probe. Piezometric pressures were measured before, one time during the storm, and after the storm to obtain general changes in the character of the equipotential lines. Lag times in the piezometers showed that the hydraulic conductivity of the sand was approximately of 80 feet per month while the silt below the channel was approximately 11 feet per month.

To determine if overland flow or interflow was occurring on the hillsides, a three-foot long interception structure was constructed. The device is shown schematically in figure 2 and evolved from a similar unit reported by Whipkey (8). Sheet metal

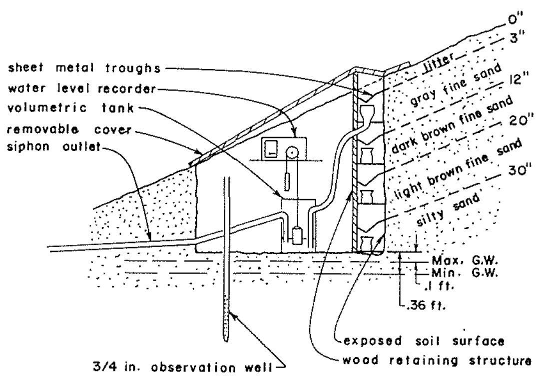


Fig. 2 — Schematic of surface and Subsurface Flow collection system.

troughs were inserted into the exposed soil surface at each apparent change in texture. It was recognized that such a device would detect only a saturated interflow, but since the unsaturated hydraulic conductivity of a sand drops so sharply with decreasing moisture content, it was assumed that any lateral movement at less than saturation would be insignificant. The trough placed immediately below the layer of litter was to collect any surface flow and deliver it to a volumetric tank equipped with a water level recorder.

Discussion

During the period of investigation, June through October, 1966, eighteen storms having a precipitation in excess of .2 inches occurred. The maximum storm had a precipitation of 1.32 inches and the maximum rainfall intensity was six inches per hour. After subtracting the rainfall interception and measuring the changes in soil moisture storage, it was found that the contributing area ranged between 1.2 and approximately 3 percent of the total watershed area. This is consistent with the literature previously cited. All of the storms have been analyzed to determine the runoff volumes involved. Seven storms have been analyzed by the proposed model of equation 4.

Figure 3 is indicative of the response of the various inflow components. This figure shows: the total inflow entering the channel; the sum of the discharges for the eight seeps along the length of the channel; the computed values of Q_L; the average flows for

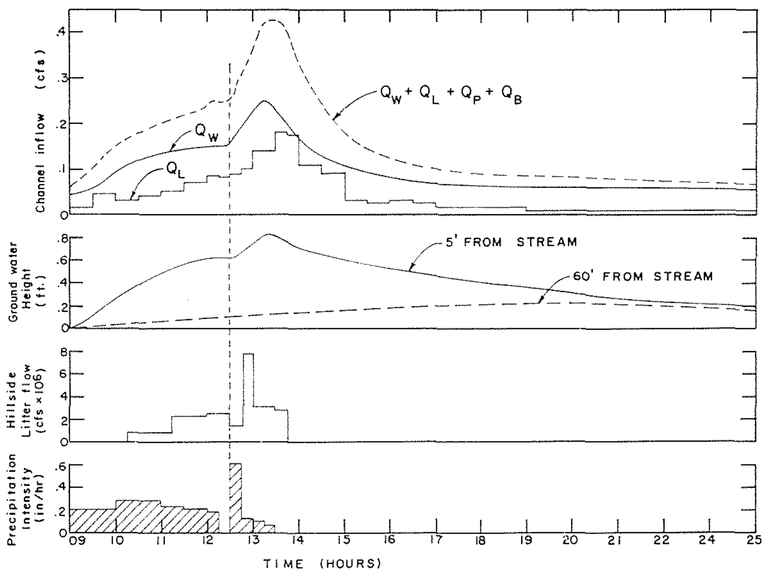


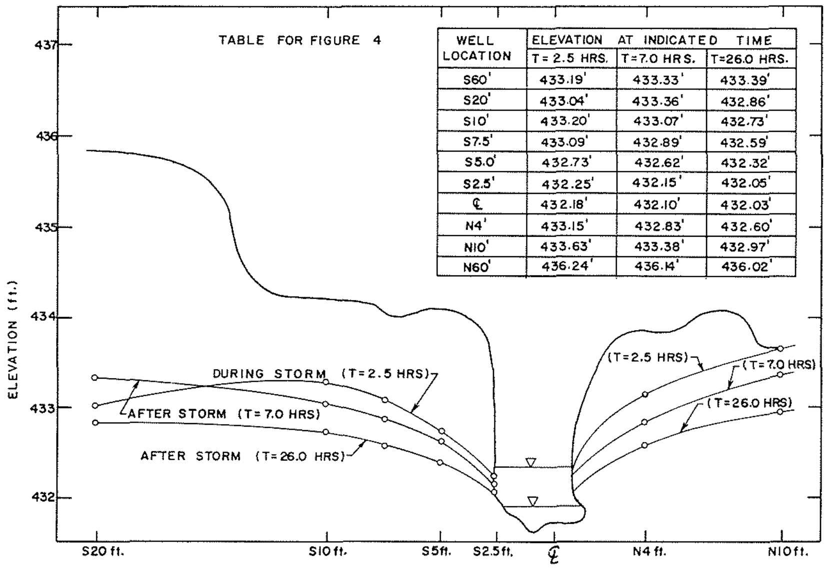
Fig. 3 — Response to storm of sept. 4, 1966, Rainfall 1.10 in. Duration 4,5 Hrs

individual time periods measured in the forest litter by the interception structure shown in figure 2; the change in elevation of the ground water table measured by recording wells at points 5 feet and 60 feet from the stream center line; and the rainfall intensity for the different time periods. Analysis of the storms by equation 4 shows that the channel precipitation varies between two and five percent of the total volume of runoff. The flow from the seeps varies from 55 to 62 percent of the runoff and the ungaged lateral inflow Q_L varies between 36 and 43 percent. These quantities are dependent on the antecedent moisture conditions and the rainfall volume, intensity, and duration. A multiple correlation analysis will be conducted to determine the details of this relationship.

The seeps were characterized by small wet areas that formed near the toe of those slopes that terminated near the stream. One seep draining into the stream, however, was formed at the toe of a slope that terminated approximately 150 feet from the channel. All seeps showed an immediate response to precipitation and, for light to moderate rainfalls, the contributing area was equal to the wet area surveyed around the seep. During an extended period of precipitation the rate of change of rainfall input was approximately equal to the rate of change of outflow from the seep. This indicated a relatively stable drainage area. It was observed, however, that at those times when flow developed in the forest litter, as measured by the interception structure of figure 2, the instantaneous rate of change in the seep discharge increased significantly and in some cases exceeded the rate of change of rainfall input. This indicated a growing watershed area resulting from flow coming down the hillside. At those times when the rainfall intensity decreased, and flow ceased on the hillside, the rate of change in discharge of the seep would immediately drop—even though it was still on the rising side of the hydrograph. This finding indicated that the drainage area contracted back to the wet area after hillside flow ceased. During these periods ground water observation wells arranged in interlocking triangles were monitored in the area of the seeps. No shifts in ground water flow toward the seeps during any period of the rainfall were detected.

The flow measured by the interception structure cannot be considered as an overland flow. The water collected was clear and did not indicate any erosional processes. The rate of flow was also very small and did not exceed 7.8×10^{-6} cfs. An investigation was undertaken to determine more of the nature of this flow. A profile was cut during one of the storms to determine if the flow was actually occurring through the needles or through a mixture of litter and decomposed organic soil immediately above the fine sand. The cross-section showed approximately 2 inches of loose, damp, pine needles followed by a 1.5 inch mixture of dark organic soil and needles. This lower layer was saturated and when squeezed water ran out quite rapidly. The uniform sand below was moist, but it was less than saturation. It was concluded that the flow was occurring as a saturated porous media flow within the lower zone of the litter. By assuming a hydraulic conductivity equal to 10 feet per month, using the slopes of the local hillside, and cross sectional areas of flow, a discharge of 2.3×10^{-6} cfs. was computed. Considerable assumptions are involved, but the magnitude of the flow is of the same order as that measured. In addition, the general behavior is consistent with the concepts of porous media flow. The flow seemed to occur after long periods of rainfall of after periods of intense precipitation which, perhaps temporarily, was in excess of the rate at which it could enter the soil. After the storage was satisfied and the media became saturated a flow developed. Since the lower boundary was on an unsaturated soil mass under negative pressures, any flow developing in this media would be subject to considerable loss due to infiltration. When the rainfall intensity decreased the losses through the lower boundary into the unsaturated media caused the flow to cease quite rapidly. When the hillside flow was occurring, however, it was computed that the entire length of the slopes would constitute approximately 10 percent of the flow entering the channel from the seeps.

As shown in figure 3 the response of the ungaged lateral inflow was quite rapid. In most storms this inflow lagged the hydrograph peak at the lower end of the channel. Under classical interpretations this would be disignated as either interflow or perhaps part interflow and part overland flow. Except for the hillsides, the micro-relief of the basin precluded any extensive overland flow. There was also an absence of soil lenses which might aid in the formation of a saturated interflow. It was observed, however, that the recording observation well located five feet from the channel responded very quickly to rainfalls. In fact, a ridge in the ground water table, similar to that observed under infiltration basins, formed along the length of the south side of the stream. This is indicated in figure 4. The formation of the ridge is explained as follows. As seen from figure 4 the ground surface breaks fairly sharply approximately 15 feet from the stream. Near the stream the ground water table is within two feet of the ground surface while at sixty feet from the stream the ground water is 8 feet below the ground surface. In the area of the high ground water table a small quantity of rainfall infiltrated the soil and converted the capillary fringe into a saturated zone and produced a very rapid, but localized, response to ground water table pictured by figure 4. As the rainfall decreased this ridge drained and produced a more typical ground water



WELL LOCATION	ELEVATION AT INDICATED TIME		
	T = 2.5 HRS.	T = 7.0 HRS.	T = 26.0 HRS.
S60'	433.19'	433.33'	433.39'
S20'	433.04'	433.36'	432.86'
S10'	433.20'	433.07'	432.73'
S7.5'	433.09'	432.89'	432.59'
S5.0'	432.73'	432.62'	432.32'
S2.5'	432.25'	432.15'	432.05'
℄	432.18'	432.10'	432.03'
N4'	433.15'	432.83'	432.60'
N10'	433.63'	433.38'	432.97'
N60'	436.24'	436.14'	436.02'

Fig. 4 — Ground water table Fluctuations Piezometer cross section one Storm of sept. 4, 1966, Rainfall: 1.10 inches, Duration: 4,5 hours, Scale: 1″ = 4′ (Horizontal) 1″ = 1′ (Vertical),

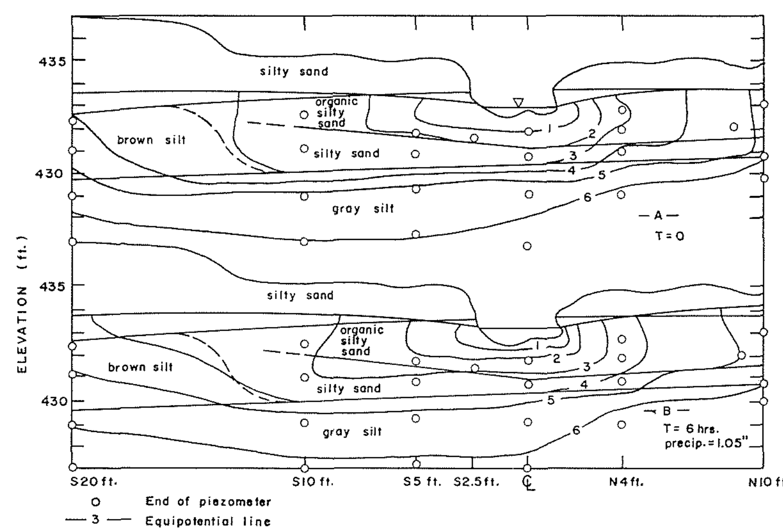


Fig. 5 — Equipotential lines before and during storm of Sept. 15, 1966,

profile. The ground water table away from the stream did not respond as rapidly because of the large depth of overlying soil. Repeated tests so check well lag-times showed all to be working properly. It was found that the latral inflow as computed from equation 4 was closely related to the depth variations recorded by the five-foot well. Using one set of data, the average drainage from this ridge and the more uniform grond water on the north side was computed as 2.6×10^{-2} cfs. During the same period the value of Q_L varied between $1.1 \times 10_{+}^{2}$ and 6.2×10^{-2} cfs.

In the storm represented by figure 3, measurements of soil moisture in the vicinity of the stream indicated that very little of the incoming rain water was stored in the mantle. Measurements of soil moisture away from the stream, at points where the ground water table was eight feet and fifteen below the ground surface, indicated that 70 percent of the through-fall was stored in the soil mantle. The experimental data also showed that the volume of the ungaged lateral inflow could be accounted for by considering the rain falling a strip paralleling the length of the channel. This strip was found to vary between 31.2 and 42 feet wide and is consistent with the experimental data. Further indications that a large flow increase occurred in the ground water table is reflected by the equipotential lines shown in figure 5. Figure 5-A shows the equipotential lines immediately preceding a storm and figure 5-B shows the equipotential lines six hours after the beginning of the storm. Very little change in pressure took place in the silty layer because this flow is controlled by conditions some distance from the stream. The potential lines became closer together in the vicinity of the stream in the upper layer of soil thus indicating a larger flow rate.

From this experiment it was concluded that no overland flow existed and all lateral inflow not measured in the seeps or determined as channel precipitation came from the rapid response of the ground water table adjacent to the stream.

Conclusion

The paper shows a feasible technique for isolating inflows and shows the results on one watershed. The paper shows that partial area contributions do exist and that the phenomenon is quite logical when the fundamentals of the individual runoff processes are considered. The results of this study and those cited illustrate that there is a serious need for a re-evaluation of some of the traditional methods used for runoff computations. Further, any parametric model developed for the synthesis of hydrologic events should be able to reflect partial area contributions.

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DISCUSSION

Intervention of Dr. P. MEYBOOM

Question:

Would the rapid response of the water table be similar to what has been described as the LISSE EFFECT?

Intervention of J. BULEK

Question:

I wonder, if the all observed area was alluvial, or if some part of that area was nonalluvial?

Answer

It was a water deposited sand resting on silt. In the largest flows there was some bed movement. There was no seepage loss to the ground from the channel as we generally assume with the classical alluvial channel since the water table at all points and all times was higher than the free surface of the channel.

Intervention of J.H. FLEMING

Question:

What were the characteristics of the vegetation over the catchement area?

Answer

The watershed was completely forested and was operated for two purposes—municipal water supply and logging. In the easily accessible, flat areas outside the stream valley, there was controlled planting and harvesting of pine. In the valley, which was not suitable for logging, there was a mixture of oak, maple, small white birch and pine.

Intervention of Henry W. ANDERSON

Question:

Did you do any tracing of water which would verify your conclusion that "no interflow in the soil mass above the water table was encountered?" Then you found no areas of relatively impermeable soil ,either at the surface or within the soil, that would cause lateral flow?

Answer

We did not add any tracers at anytime. Our flow collection system that cut through the soil mass on the hillside would have detected any saturated movement—as it did at the surface. We could not with this device, however, detect any lateral movement occurring as an unsaturated porous media flow. There was not sufficient soil stratification to create any "perched" saturated zones. We were able to detect vertical movement of water through the unsaturated soil mass through the use of single tube neutron meters. It is very doubtful that any significant unsaturated flow moved laterally because this was a fine sand and thus had the characteristic rapid drop in hydraulic conductivity as the percent saturation decreases.

Intervention of L.L. HARROLD

Question:

On the steep forested areas, there was surface flow during periods of very high rainfall. Were there places where this flow failed to reach the stream—that is, did it seep into the sandy soil?

Answer

The major portion of this flow reached seep areas at the tops of the slope and then moved on the stream. Where the slope terminated on the flat flood plain, we had no indication that the flow continued on to the stream. I think the nature of this flow precluded the continuation across the flat plain. As stated in the paper, this was a porous media flow taking place in a thin layer at the base of the forest litter. As a result it was found only in those areas where there was a substantial gradient. Thus, in the flat areas, it simply infiltrated into the soil.

Intervention of William C. ACKERMANN

Question:

You had many instrument in your watershed, how was the time of these synchronized?

Answer

Time agreement within one minute was achieved by synchronizing all times before a storm. It was only possible because the investigators lived on the watershed.