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THE ANALYSIS AND APPLICATION OF A DIGITALLY SIMULATED ELECTRONIC WATERSHED ANALOG

Richard M. Tinlin and John L. Thames[1]

ABSTRACT. A digitally simulated electronic watershed analog has been developed for the analysis of the hydrologic regime of a watershed. Individual electrical circuits were designed to synthesize the physical characteristics of the hydrologic components of a watershed: interception, surface storage, runoff, infiltration, and subsurface storage. These circuits were related to pertinent empirical studies of significance to each component. Electrical circuit analogues despite definite advantages inherent in their direct physical correspondence to systems of significance to hydrology, have fallen into disuse due to the inflexibility of fixed component networks. A digital simulation program developed by the electrical engineering profession to provide flexibility in the design of electronic circuitry has been adapted for the simulation of the electronic watershed analog. The typical digital circuit analysis program is "canned" and the user need not understand its intricacies. Input is in the form of circuit parameters on punched cards. The output is in numeric or graphic form. Using digital simulation methodology the electronic watershed analog has been used to analyze a 1.63 acre forested watershed.

(KEY WORDS: digital simulation; electronic watershed analog; hydrology)

INTRODUCTION

Watershed modelers are faced with two conflicting requirements in selecting a model for the simulation of watershed hydrologic processes. The first is to select a model which is as descriptive as possible, and the second is to avoid over-complexity. The electric watershed analog described in this report provides an excellent compromise. The flow of electrical charge on one hand and the flow of water on the other provides the analogous link between the two systems. The electrical circuit serves as a mathematical shorthand to transform an otherwise highly complex set of integro-differential equations to a much lower level of difficulty.

The analog was built step by step to synthesize the physical structure of a watershed in relation to hydrologic processes as presently understood. Empiricisms developed over the years were then related to the electrical circuitry of the analog.

Analyses of the analog were made using ECAP, a versatile digital electric circuit network analysis program developed by IBM (Jensen and Lieberman, 1968). The technical and theoretical capability of electrical circuit analysis methods undoubtedly exceeds our mastery of watershed systems analysis. Once a transformation to the electrical format has been made, the analogous watershed system can be easily subjected to exhaustive parameter modification tests on the digital computer. The major consideration is, then, how accurately the analogous electrical circuit describes the physical system. Particular attention is paid this factor in the study.

Briefly, ECAP is an integrated system of four programs developed to aid in the design and analysis of electronic circuits. The four programs consist of: (1) an input language, (2) DC analysis, (3) AC analysis, and (4) transient analysis. Only the input language and transient analysis programs were used in the analyses. The input language is user-oriented and allows complex circuits to be easily formatted for computer analysis. The transient analysis program provides the time response solution of linear or nonlinear electrical networks subject to arbitrary user-specified driving functions. ECAP, in addition to being an effective electronic circuit simulator, is also used in analyzing other physical systems that have corresponding electrical network analogs.

The validity of the watershed analog was tested using data collected by the U. S. Forest Service on a 1.63 acre forested watershed located in central Arkansas (Rogerson, 1971). The watershed modeled is one of three adjacent similar catchments. The vegetation on the watershed consists of a shortleaf pine overstory and a mixed hardwood understory. Pine-hardwood litter covers the forest floor to a depth of about 2 inches. The soils are shallow, about 3 feet deep, and moderately permeable, with a low waterstorage capacity.

[1]Instructor and Professor of Watershed Management, University of Arizona, Tucson, Arizona.

MODEL DEVELOPMENT

The aim of this research has been to develop a general purpose hydrologic model for small watersheds. All of the major hydrologic land phase components were included: interception, surface depression and litter layer storage, runoff, infiltration, near surface soil moisture storage, interflow, loss to groundwater, and evapotranspiration losses. A descriptive model was used as a reference framework for the basic model concept. A forested watershed was selected as a basic unit of study, however the principles derived may be readily applied to a variety of other watershed types.

The basic descriptive unit is shown in Figure 1. The total rainfall component is subdivded into intercepted rain and direct throughfall. There are three interception subcomponents: indirect throughfall, stemflow, and subtransient leaf storage. Subtransient leaf storage is the precipitation that remains in storage to be later lost by evaporation. Evaporation losses from the storage zones are controlled externally by the energy available to stimulate the process, ceasing only when no storage exists. Indirect throughfall is the component of total rainfall which passes directly through the canopy or open spaces to the ground with no interference. Direct throughfall combined with indirect throughfall and stemflow form

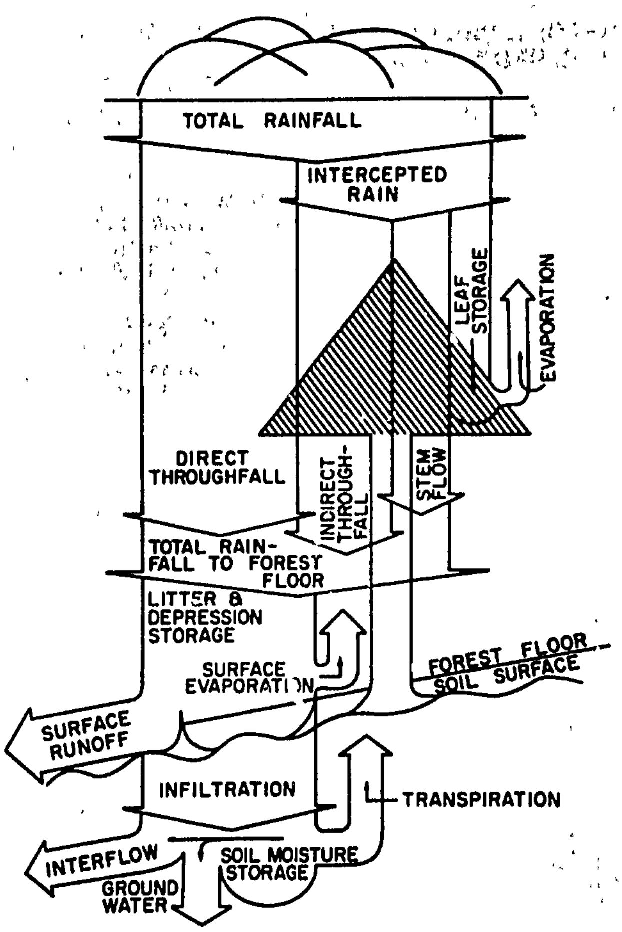

Figure 1, The Descriptive Model

the total rainfall input at the forest floor after modification due to storage lags and evaporation losses.

The precipitation reaching the forest floor has been divided into five subcomponents: infiltration, litter storage, surface depression storage, surface runoff, and evaporation from litter layer storage. The infiltration component is subdivided into near surface soil moisture and interflow. Near surface soil moisture storage is subject to transpiration and groundwater losses. The magnitude of the groundwater component is a function of soil moisture storage.

This modeling concept is presented making the following assumptions as related to the descriptive unit: (1) the physical characteristics of the element are time invarient; (2) the descriptive unit has essentially the characteristics of a unit-source area, defined by Amerman (1965) "as having single cover, a single soil type, and otherwise physically homogeneous".

The interaction between the major components of the descriptive model can be illustrated by using a hydraulic model composed of storage reservoirs as shown in Figure 2. Flow between reservoirs follows the same paths as those in the descriptive model, but gives a clearer view of how the system operates. Time lags are

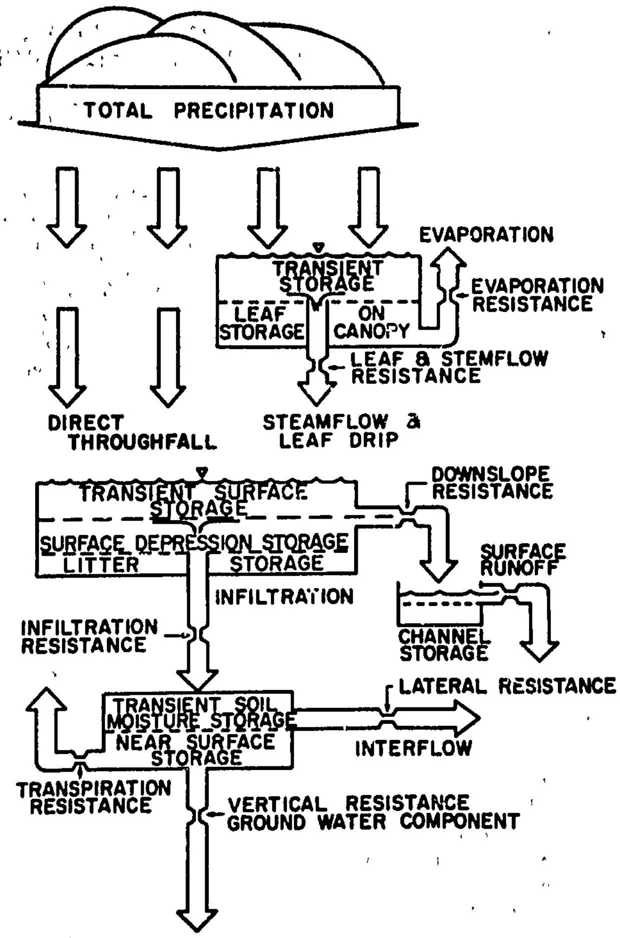

Figure 2, The Hydraulic Model

built into the model since finite time intervals are required to fill the storage reservoirs.

The reservoirs representing surface depression storage and litter storage are stacked in the sense that litter storage must be satisfied before surface depression storage can fill. Litter storage must also be satisfied before infiltration occurs.

Infiltration commences when the litter layer has become sufficiently wetted, and continues throughout the event. After the event ends the surface depression volume will continue to infiltrate into near surface storage until it is depleted. The constriction in the infiltration arrow signifies a resistance or conductivity factor in series with a soil moisture capacity zone. The transpiration arrow indicates that a portion of this storage is allowed to bleed off, by an amount proportional to an external transpiration function.

Once surface soil moisture storage is raised to field capacity, lateral flow (interflow) will commence. Vertical and lateral resistance controls are included to proportion the amount of flow in each direction. Interflow in the lateral direction combines with surface flow while vertical flow passes on to groundwater storage.

When surface depression storage requirements have been met, surface runoff commences. Downslope friction to overland flow causes transient storage to build up over the surface depression storage area. This transient storage decays off as surface runoff at the end of the storm event, and is routed through channel storage.

The hydraulic model results in a lumped-distributed system closely related to the actual physical system of interest. The descriptive unit is lumped in the horizontal plane and distributed vertically in the sense that three separate reservoirs are used to model the downward flow sequence. The model has been designed to serve as a basic building block for which parallel-series combinations can provide a technique for complex watershed problem analysis.

THE ELECTRICAL ANALOG

The use of digital simulation techniques allows nearly complete freedom in the selection of network component values for the electrical analog. In actual practice, a one farad capacitor is physically unrealistic, but presents no problem using digital simulation methods since the capacitor value is defined numerically. Expensive electronic hardware such as function generators can be simulated with a few punched cards.

The primary components of the electronic watershed analog are resistors, capacitors, and diodes. The resistors are used to restrict flow, and in other instances are combined with capacitors to determine decay rates for recession curves. The capacitors are used to simulate storage. Diodes serve as electrical check values directing current flow and holding charge on the capacitors. To provide driving functions both dependent and independent current sources are used. Current transfer between the passive circuit elements and the current sources is accomplished by using transfer function or T-cards, a very useful feature of ECAP.

The Interception Analog

The electrical circuit for interception is shown in Figure 3. By relating to the basic model concept for interception discussed earlier, the interception circuit can be analyzed. The input to this circuit may be a constant current pulse or a time varying function which simulates an actual storm. The rainfall generator is designed to provide either. Validation of the interception analog was made with the empirical relationship developed by Grah and Wilson (1944).

Grah and Wilson conducted interception studies on selected specimens of Monterey pine and Baccharis (an evergreen shrub). The plants were suspended from a balance in a sheet metal chamber and sprayed with water. Changes in surface detention were determined at one-minute intervals. At the end of the simulated rain the excess water was allowed to drip from the foilage and stems, resulting in a second value which may be compared to the maximum interception under field conditions.

The physical relationship between the analog and this classic experiment was used to analyse the buildup of detention storage on plant surfaces. Mathematically the

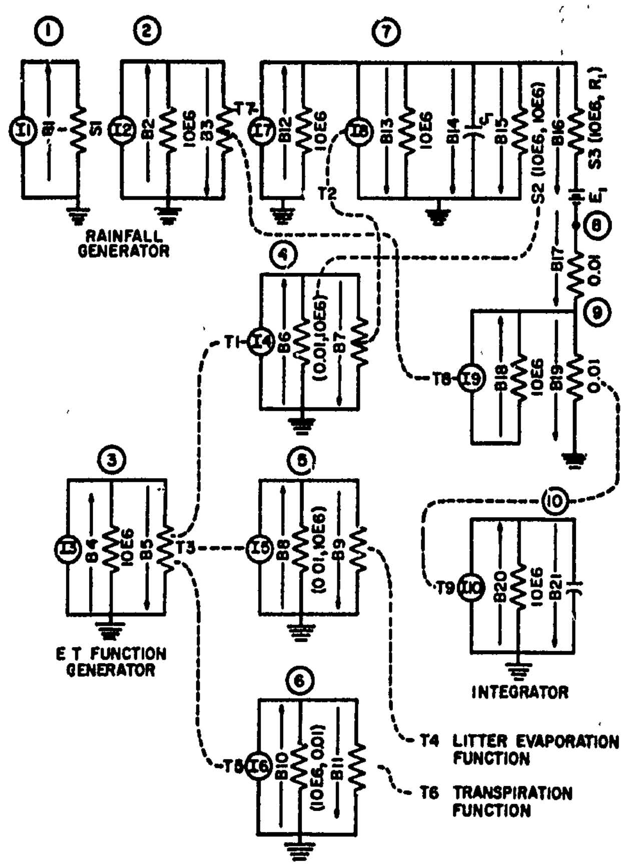

Figure 3, The Interception Analog

circuit of the interception electric analog can be described in a manner compatible with the empirical developments, indicating that the mechanisms governing the interception process have a close analogy to the physical laws governing the behavior of the interception analog.

The interception analog was applied to the Arkansas watershed. The source of the model parameters are reports by Lawson (1967) and Rogerson (1971).

The lag times for actual watershed canopies are unknown but there is ample evidence that they do exist. Realistic values are probably on the order of a few minutes. Under dense canopy conditions it is possible that these lags are sizable and would then exert a pronounced effect on the rainfall prior to reaching the forest floor. The result could be a significant modification of the runoff hydrograph.

The storm used in this test occurred on the Arkansas watershed in December of 1968 and is herein identified as the calibration storm. A plot of the rainfall and throughfall in Figure 4 illustrates the modification in the time distribution of rainfall due to the forest canopy. The leading portion of the rainfall event is markedly reduced due to initial interception losses.

The Surface Storage and Runoff Analog

The circuit used to describe the runoff phase of the analog is in principle much the same as the interception analog circuits. Figure 5 shows the combined surface runoff and infiltration electrical component arrangement

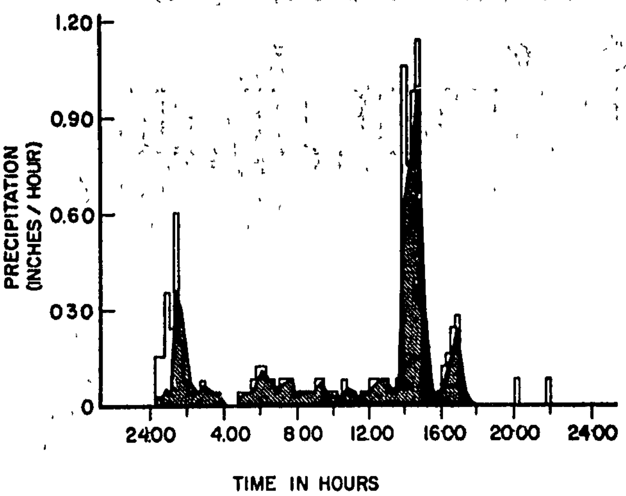

Figure 4. The Modification in the Time Distribution of Rainfall by the Forest Canopy

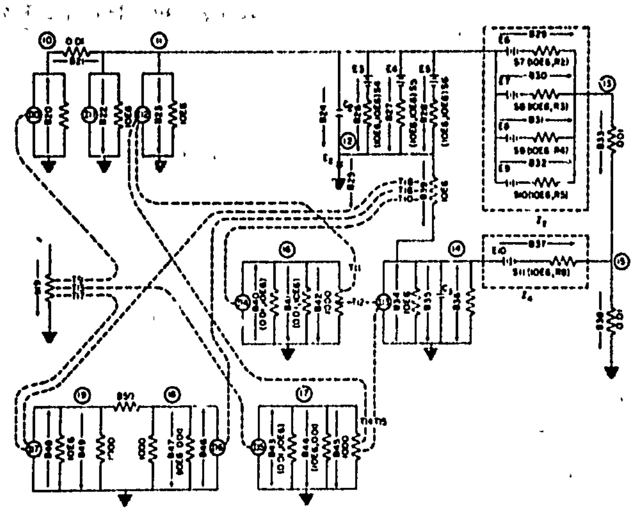

Figure 5. The Combined Surface Runoff and Infiltration Analog Circuits

in ECAP format. The surface runoff analog was fitted to the experimental overland flow data of Izzard (1946). Izzard's study demonstrated that surface runoff is characterized by a nonlinear storage-outflow relationship. The source of this nonlinearity, assuming no infiltration, is the manner in which surface friction or viscous drag varies in response to a number of influencing variables such as surface slope, surface channelization, and surface storage characteristics.

To date there has not been developed a suitable overland flow equation which is applicable to a forested watershed with the above confounding characteristics. On the other hand, a hydrograph under certain ideal conditions, namely an abrupt beginning or end to a spatially uniform high intensity storm, contains a signature, unique to a given watershed, which can be used to define the nonlinear manner in which surface friction varies.

A modified version of the surface analog circuit was devised to reconstruct the current vs. voltage relationship or by analogy outflow vs. water depth on Izzard's test plot. The function of the circuit was to input the simulated rainfall into a capacitor simulating the area of the test plot and extract an outflow equal to that observed during the experiment. The result is that a voltage builds up on the storage element analogous to the water depth on the test plot at corresponding times during the experiment.

Since the depth of water on Izzard's plot at any time is analogous to voltage (V) and the outflow (Q) is analogous to current (I), an I vs. V relationship was developed (Figure 6). A piecewise linear approximation consisting of four connected straight-line segments was then superimposed on the rising limb of the I-V relationship. Since the relationship between current and voltage is resistance, the nonlinear I-V curve represents the nonlinear resistance in opposition to overland flow for Izzard's study. Jensen and Lieberman (1968) give a detailed discussion of piecewise approximation methods.

The surface analog circuit, with the determined nonlinear resistance or diode model in place, was used to evaluate Izzard's experiment. The analog output for two rainfall intensities, 3.60 in/hr. and 1.89 in/hr. is plotted against Izzard's observed values in Figure 7a. The higher intensity event fits very well on the rising limb but poorly on the recession limb. The lower intensity event fits poorly on both limbs of the hydrograph. Figure 7b shows the result of fitting the diode model to the recession limb of Izzard's hydrograph. At the higher intensity the rising

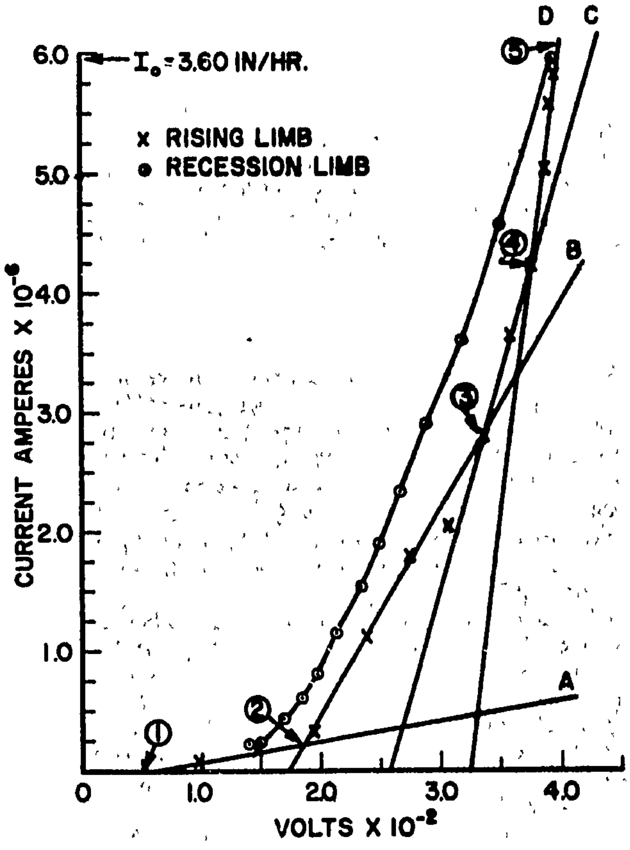

Figure 6, Piecewise Approximation to I-V Curve for Izzard's Experiment

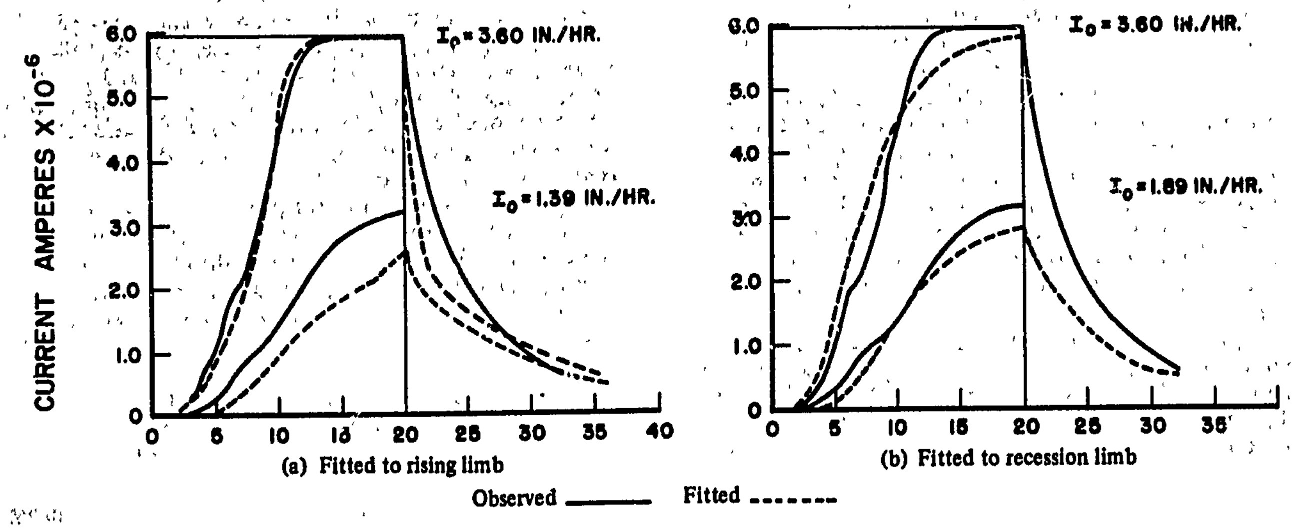

Figure 7, Izzard's Data Fitted by Nonlinear Diode Model

limb fits moderately well but there is a perfect fit on the recession limb. A better fit also exists for the lower intensity event.

The anomaly between the rising and falling limbs is normally attributed to turbulent flow during the runoff event. It has been suggested by Riley et al (1967) that the effects of inertia and momentum are negligible for a watershed system unless relatively high velocities are encountered such as channel flow. It may well be that these considerations are the actual cause of the discrepancy between the rising and falling limbs of Izzard's hydrograph.

The storm selected for calibration of the interception analog was also used to calibrate the surface storage and runoff analog. The depth of storage on the surface storage element was computed using ECAP as was done for Izzard's experiment. The observed outflow data were then plotted against the computed storage depths to form an I–V curve. The data were incorporated in the surface runoff analog as a nonlinear diode model. Then the combined interception and surface runoff analogs were used to analyze the calibration storm. With the exception of surface depression storage no parameter adjustment was necessary to obtain the computed hydrograph of Figure 8. The computed hydrograph is larger than the observed since at this point infiltration has not been included. Nevertheless an excellent similarity in shape exists between the simulated and observed hydrographs.

Infiltration and Subsurface Storage Analog

Empirical evidence by Horton (1933) and Holtan (1961) indicates that the infiltration rate is a function of the soil moisture deficit, assuming that the supply rate exceeds the potential or instantaneous infiltration rate. To fully demonstrate the infiltration analog it was necessary to combine it with the surface storage and runoff analog. The combined analogs are shown in Figure 5. Mathematically the infiltration analog is identical in form to Horton's infiltration equation.

The infiltration analog has been designed to compare the infiltration source, rainfall or surface depression stor-

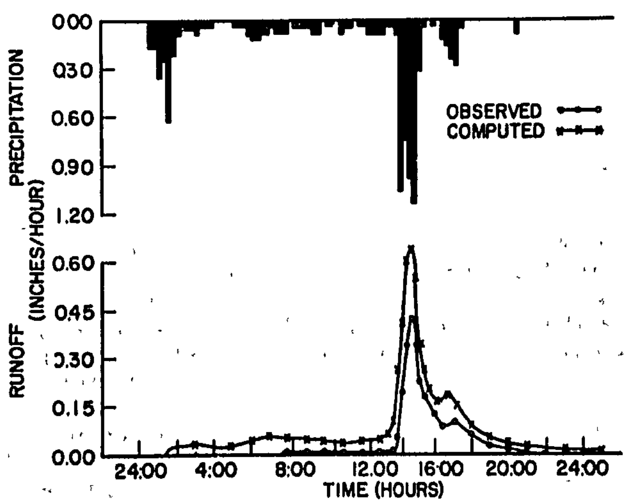

Figure 8, Comparison of Observed Hydrograph with Computed Hydrograph of the Calibration Storm, Infiltration Excluded

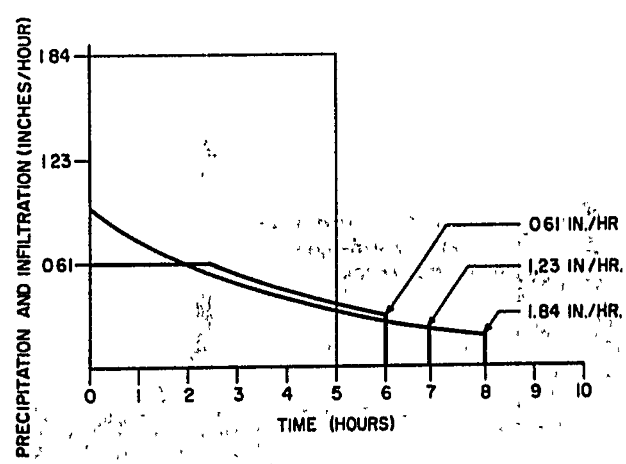

Figure 9, Infiltration in Response to Simulated Increases in Rainfall Intensity age, with the potential infiltration rate. When the comparison has been made, the smaller value of the two is used to drive the infiltration process

To demonstrate how the infiltration analog responds to increasing rainfall intensities and changes in antecedent soil moisture, a number of tests were conducted using the anlog. In order to conduct these tests, the scaling applicable to the Arkansas watershed was used. The rainfall generation circuit of the combined surface and infiltration analog was modified slightly to generate a step function output to simulate abruptly starting and stopping rainfall.

The manner by which infiltration on the watershed responds to step increases in simulated rainfall is illustrated in Figure 9. Although the simulated rainfall event ends abruptly, infiltration continues until surface detention and depression storage are depleted. At higher rainfall intensities there are greater rainfall excesses and as a result it takes longer to deplete surface storage.

The 1.23 and 1.84 inch/hour events exceed the maximum potential infiltration rate. They therefore have a common infiltration curve except that at the 1.84 inch/hour rate, surface depression depletion takes longer. This curve is different from that resulting from the 0.61 inch/hour rate because at the higher intensities, soil storage is being filled at its maximum rate.

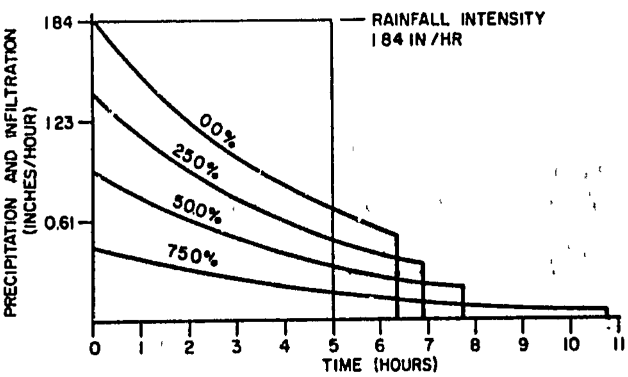

Figure 10, Infiltration in Response to Antecedent Moisture

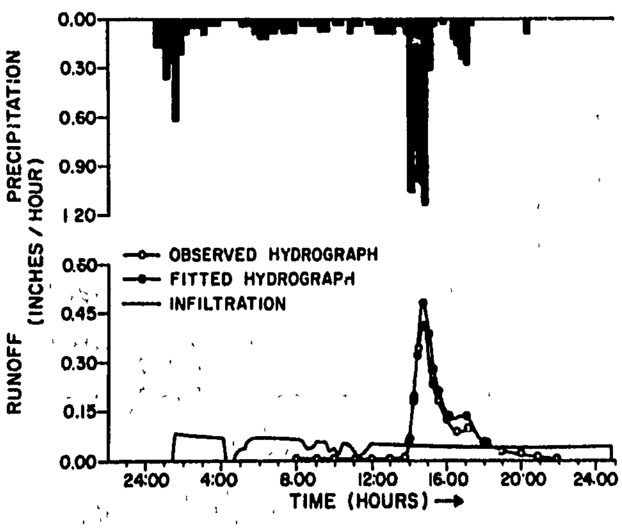

Figure 11, The Observed and Computed Hydrographs for the Calibration Storm with the Infiltration Analog in Operation

Figure 10 illustrates the effect of antecedent charge on the infiltration rate. The rainfall intensity was held at 1.84 inches/hour for 5 hours for each simulated antecedent charge. With higher antecedent charge conditions and correspondingly smaller infiltration rates, larger surface storages accumulate which require greater post-event infiltration periods.

The result of adding the infiltration circuit to the interception and surface analog circuits is shown in Figure 11. The observed and fitted hydrographs show excellent agreement in both shape and timing. The total volume for the computed hydrograph is also very close.

THE APPLICATION OF THE INTEGRATED ANALOG CIRCUIT TO THE ARKANSAS WATERSHED

To test the uniqueness of the parameters derived during the calibration of the analog to the Arkansas watershed, an independent storm which occurred five days earlier on the same watershed was analyzed. This storm is herein identified as the test storm. Antecedent storaged were adjusted to actual field values determined to exist just prior to the storm.

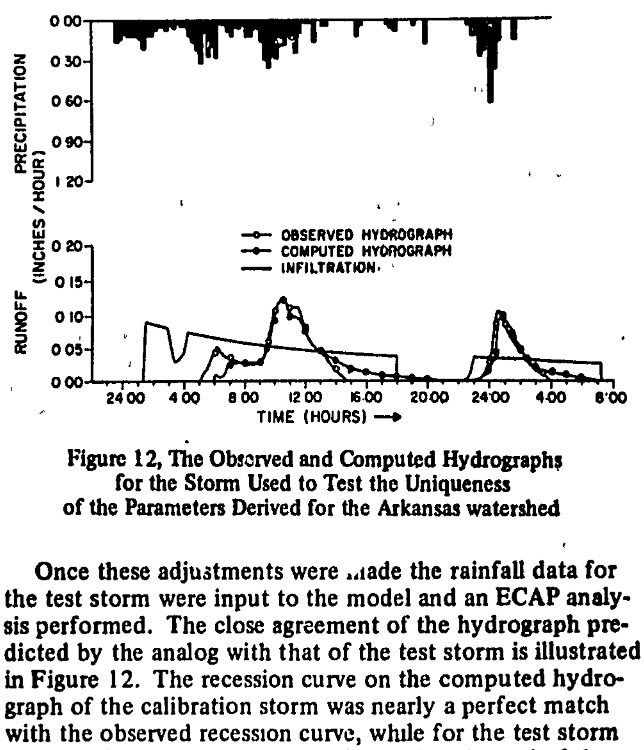

Figure 12, The Observed and Computed Hydrographs for the Storm Used to Test the Uniqueness of the Parameters Derived for the Arkansas watershed

Once these adjustments were made the rainfall data for the test storm were input to the model and an ECAP analysis performed. The close agreement of the hydrograph predicted by the analog with that of the test storm is illustrated in Figure 12. The recession curve on the computed hydrograph of the calibration storm was nearly a perfect match with the observed recession curve, while for the test storm considerable separation can be observed at the end of the recession curves of both of the storm peaks. Subsequent analysis revealed that reducing the soil moisture deficit corrected the separation in the recession curves, but resulted in even a larger error on the leading edge of the hydrograph. This led to a reexamination of the calibration storm where it was observed that increasing surface depression storage or increasing the initial infiltration rate had the same effect on the leading edge of the hydrograph. The higher initial infiltration rates charge up soil moisture

storage early resulting in lower rates toward the ends of rainfall events, lengthening the recession curves. Surface depression storage and the initial infiltration rate were the only model parameters for which field data was lacking. If infiltration data and surface depression storage estimates were available, the calibration of the analog would consist only of deriving the nonlinear surface friction component using the technique applied to analyze Izzard's experiment.

The model has been designed with a built in step function rainfall generator. This feature was used to subject the field system by analogy to hypothetical inputs to examine the Arkansas watershed nonlinear response characteristics, such as was done by Amorocho (1961) using a mechanical rainfall simulation device.

One of the tests performed by Amorocho was with a succession of three simulated square wave rainfall inputs for the purpose of observing the magnitude of the resulting departures from linearity in the output. It was observed that the three resulting output peaks of the test differed markedly in shape from one another, and that a linear superposition based on the response to a single pulse underestimated the output during the latter part of the sequence.

The nonlinear behavior in runoff of the Arkansas watershed is evident in Figure 13 in response to a series of simulated step function inputs. The interval of separation between each square wave input was made large enough so the successive outputs would not overlap. The simulated runoff totals for each of the three peaks were 1.49, 2.11, and 2.48 inches respectively. The recession curves for the simulated hydrographs can be seen to be highly influenced by the lower infiltration rates toward the end of the test. The indentation in the leading edge of the first hydrograph creating the characteristic S-shape is the result of the high initial infiltration rate which decreases with time.

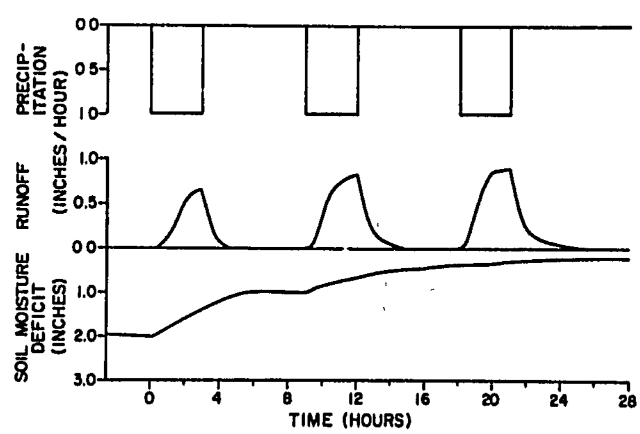

Figure 13, Nonlinear Response of the Arkansas Watershed to Simulated Step Function Rainfall Inputs

CONCLUSION

The major intent of this study has been to develop an electronic watershed analog with a direct physical correspondence to the hydrologic regime of a watershed, capable of synthesizing the major hydrologic characteristics of a watershed. The use of digital network simulation methodology has made this possible.

The basic analog unit developed is readily amenable to use as a basic unit in larger lumped-distributive models describing larger watershed systems. More powerful and efficient digital network simulation methods, e.g., SCEPTRE (Bowers and Sedore, 1971) are available and have the capacity to treat the basic analog unit in iterative fashion allowing a watershed to be subdivided to compensate for the distributive variability apparent in watershed parameters.

Optimization techniques are also available for electrical circuit design which can be used to facilitate calibration of rainfall events for evaluation of undetermined parameter values. An example of such a program is GOSPEL, a General Optimization Software Package for Electrical network design (Huelsman, 1970).

It is possible using this model to investigate properties of small watershed systems in depth which are unmeasurable in the physical system. The effect of treatments such as clear cutting on the hydrologic regime of a watershed may be evaluated in advance of the actual implementation of the treatment. The apparent high accuracy of the model allows the investigation of the effect of subtle influences resulting from evaporation and transpiration losses during rainfall events as well as the dynamic adjustment of the watershed system during the intervals between storms.

A capacity for handling precipitation in the form of snow can readily be built into the model. In addition, it is possible to define the electrical circuit in mathematical terms, and thereby define the watershed system mathematically. One of the more exciting areas of application is in the classroom. The direct analogy and scaling provides students with no special training in computer programming the opportunity to study watershed interrelationships in a most realistic manner.

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