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Infiltration and Soil Moisture Redistribution in HEC-1*

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INTRODUCTION

The U.S. Army Corps of Engineers' water resource modeling efforts have been motivated by the civil works needs of the Corps field offices. The main responsibilities of the Corps of Engineers have been in flood control and navigation, and thus the models were developed to meet those needs. Hydrologic analyses for flood control typically involved flood frequency and duration, spillway discharge, reservoir storage, channel and floodway capacity, water surface elevations, flow velocity, and flooded area computations.

Because of this primary interest in flood control and, therefore, the larger, damaging flood events, the Corps' Hydrologic Engineering Center (HEC) chose to simulate flood hydrographs with a so-called single-event watershed model. The "HEC-1 Flood Hydrograph Package" (Corps, 1981) simulates single flood events, although that one event may occur for many days or months in a complex river system. No soil mositure accounting is made between flood events.

More recently, however, HEC-1 is used for design flood simulation and flood forecasts. In the flood forecast mode, HEC-1F (forecast version) uses a feedback loop to update current soil moisture conditions as the flood event progresses. The update methodology is a parameter fitting process which mininizes the differences between the observed and computed runoff. The primary parameter fitted in this manner is the initial soil moisture deficiency.

SOIL MOISTURE'S PLACE IN A RIVER BASIN MODEL

What are the major factors which bring about the shape and size of a hydrograph? How important are these factors? Which factors does one have the most confidence in estimating? These are questions the hydrologic modeler must ask in the effort to simulate the occurrence of a flood event.

There are four main factors which determine the size and shape of a hydrograph.

1) Precipitation rates and spatial distribution.

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2) Interception/infiltration rates and spatial distribution.

3) Transformation of rainfall/snowmelt areal excess into stream runoff, and

4) Routing the runoff through rivers.

The volume of runoff is determined by the first two factors while all four contribute to the shape of a hydrograph.

Streamflow is probably the best known (measured) component of the rainfall-to-runoff process. Less is known about rainfall and catchment loss rates. Rainfall studies indicate that there is potential for larger errors in point measurement of intensity and that the spatial variability of the process can be quite large. For example, Neff (1977) indicates that measurement of rainfall intensity may differ by as much as 70% between surface and pit gages (the difference attributed to wind effects) and Woodley et al. (1977) indicates that rain gages only a few miles apart have known to differ as much as fifty percent in their measuremet of total storm precipitation.

Catchment loss rates are a function of both surface conditions (initial abstraction and depression storage) and soil hydraulic properties (infiltration capacity). Smith (1982) discusses the need to characterize the effects of rooted plants, crusting and cracking on infiltration processes and Woolhiser (1982) indicates the need for additional research to characterize depression storage. Although much work has been done theoretically to describe infiltration into a homogeneous soil, field measurement indicate that the soil hydraulic properties which control the infiltration process demonstrate a great deal of spatial variability. For example, Nielsen and Warwick (1980) summarize recent field investigations which indicate that the hydraulic conductivity at natural saturation and the unsaturated hydraulic conductivity have coefficients of variation on the order of 100%.

Our knowledge of the hydraulics of open channel flow make the routing process relatively well known. Although the flow is anything but what is assumed in the theory, the one-dimensional river process is easier to simulate than the wide spatial variation of the rainfall or interception/infiltration process. The rainfall excess transformation by unit graph or kinematic wave is difficult to estimate for large areas. But, if smaller subbasins are used, these factors become less important and more importance is placed on the better known channel routing hydraulics.

The hydrologic modelers' task is to put these processes together to reproduce observed runoff in a river basin. Then, more importantly, to use that same model to predict runoff in ungaged areas. To understand these processes, and the relative importance of one versus another during any particular flood event, one must be a hydrologic detective. The storm track, spatial variation in rainfall and infiltration rates and hydraulic regime of natural and man-made features of the watershed must all be considered. Too often the hydrologic modeler just specializes in understanding one of the factors contributing to the hydrograph. Very simplifying assumptions are made about the complex processes occurring on either side of the one where the expertise is being applied. Elegant mathematical formulations are made for homogeneous, isotropic representations of the physical process. Then those formulations are applied to heterogeneous, anisotropic conditions with poorly defined input and little concern for the next step with the output.

Thus, the infiltration processes discussed in the following section should always be kept in perspective with respect to the other parts of the hydrograph formation process. The rainfall excess is the desired result of this part of the process. That excess can be changed by varying the incoming rainfall and/or the interception/infiltration. However it is accomplished, the volume of the various surface, subsurface and ground water excesses must be equal to the observed hydrograph less previous base flow.

The following discussion describes the interception/infiltration, soil moisture redistribution, soil evaporation and aquifer recharge component of these hydrologic processes. In defining this part of the process, let us keep in mind how well we know (measure) the spatial and temporal distribution of precipitation and the heterogeneous mixture of land cover and soil types we have in a natural and/or man-influenced watershed.

HEC-1 INFILTRATION PROCESSES

The main purpose of the "HEC-1 Flood Hydrograph Package" (HEC, 1981) is to simulate the hydrologic processes during flood events. The precipitation (rainfall, snowfall/melt) to runoff process can be simulated for large complex watersheds. The Corps of Engineers uses this model as a basic tool for determining runoff from various historical and synthetic (or design) storms in planning flood control measures. HEC-1 has several major capabilities which are used in the development of a watershed simulation model and the analysis of flood control measures. Those capabilities are the following:

Automatic estimation of unit graph, interception/infiltration and streamflow routing parameters.

Simulation of complex river basin runoff and streamflow.

River basin simulation using a precipitation depth-versus-area function.

Computation of modified frequency curves and expected annual damages.

Simulation of flow through a reservoir and spillway for dam safety analysis.

Simulation of Dam Breach Hydrographs.

Optimization of Flood Control System Components.

The automatic parameter estimation capability determines subbasin runoff parameters by a univariate search procedure. The unit hydrograph and interception/infiltration rates (hereafter referred to as precipitation loss rates) may be determined for individual storm events based on observed precipitation and streamflow data for a single subbasin. Streamflow routing parameters may also be determined from known inflow and outflow in a river reach.

Watershed precipitation-runoff simulation is the main function of the program and the basis for the other capabilities. The watershed model as referred to in this discussion includes all aspects of the precipitation and runoff computations necessary to simulate streamflow in the headwaters of complex river basins. HEC-1 does not take into account the effect of downstream boundary conditions. This limitation may be overcome by using hydraulics models to provide the flood routing relationships for HEC-1. Keeping this limitation in mind, the model may be used to simulate runoff in a simple, single-basin watershed or in highly complex basins with a virtually unlimited number of subbasins and routing reaches in which interconnections may exist.

Description of the Physical System

The HEC-1 watershed model uses spatially and temporally lumped (or averaged) parameters to simulate the precipitation and runoff process. The time and/or space discretization may be changed by modifying the size of subbasins, routing reaches, and/or the computation interval. There are virtually no limitations on the sizes of the components or the computation interval. The user selects the sizes of these variables that are consistent with the accuracy desired in the computational results, the allowable modeling efforts, project budget, and the available data.

Two important factors should be noted about the precipitation loss computation in the model. First, precipitation which does not contribute to the runoff process is considered to be lost from the system. Second, the equations used to compute the losses do not provide for soil moisture or surface storage recovery. (The Holtan loss rate option is an exception in that soil moisture recovery occurs by percolation out of the soil moisture storage.) This fact dictates that the HEC-1 program is a single event oriented model.

The precipitation loss computations can be used with either the unit hydrograph or kinematic wave model components. In the case of the unit hydrograph component, the precipitation loss is considered to be a subbasin average (uniformly distributed over an entire subbasin). On the other hand, separate precipitation losses can be specified for each overland flow plane in the kinematic wave component. The losses are assumed to be uniformly distributed over each overland flow plane.

In some instances, there are negligible precipitation losses for a portion of a subbasin. This would be true for an area containing a lake, reservoir or impervious area. In this case, precipitation losses will not be computed for a specified percentage of the area labeled as impervious.

There are four methods (Table I) that can be used to calculate the precipitation loss. Using any one of the methods, an average precipitation loss is determined for a computation interval and subtracted from the rainfall/snowmelt hyetograph. The resulting precipitation excess is used to compute an outflow hydrograph for a subbasin.

TABLE I

HEC-1 INTERCEPTION/INFILTRATION METHODS

Method	Parameters	Description
Initial and Constant	Initial volume loss and a constant infiltration rate	Initial loss is satisfied, then constant loss rate begins.
HEC Exponential	Infiltration rate, antecedent moisture condition, rate of change of infiltration with wetness	Initial infiltration rate adjusted for antecedent conditions and continuous function of soil wetness.
SCS Curve Number	Curve Number from land use and hydrologic soil type	Initial interception loss satisfied before computing cumulative runoff as a function of cumulative rainfall.
Holtan	Infiltration rate capacity, available soil moisture storage	Infiltration rate computed as exponential function of available soil moisture storage and is limited by ultimate infiltration rate for saturated soil.

Initial and Constant Loss Rate Method

The initial and constant loss rate function (Linsley et al., 1975), is the simplest form of all loss rate functions. The loss L, in millimeters (inches), for a time interval Δt, in hours, is:

$$L = \begin{cases} P & \text{if } L < I \\ C\Delta t & \text{if } L > I \end{cases} \qquad (1)$$

where I is an initial loss, in millimeters (inches), representing antecedent soil moisture conditions and interception losses; C is a constant loss rate, in millimeters per hour (inches per hour), which is representative of soil moisture infiltration; and P is the rainfall/snowmelt in millimeters (inches). If I is satisfied during a time interval, C applies only to the remainder of that time interval after I is satisfied. The C is also referred to as the Ø index (if I is zero) and represents the average infiltration rate, throughout the entire storm event, which produces the observed precipitation excess for that storm. Precipitation excess is that part of the precipitation which results in runoff during that period and is not lost to interception/infiltration. The initial loss and constant loss rate are often used in synthetic (design) storm runoff simulation and where inadequate data are available to justify use of the more complex methods.

HEC Exponential Loss Rate Method

The HEC exponential loss rate function simulates the interception/ infiltration process as a function of accumulated soil moisture (losses not available for runoff) as shown in Figure 1. The parameters of the method represent the effects of depression storage, D, infiltration rates, S and R, and the nonlinearity in the loss rate precess, E. The effects of soil moisture conditions are accounted for my adjusting the interception and infiltration rates by the accumulated loss C, resulting in two loss rate factors DK + AK. The loss rate factors are combined with the effect of precipitation intensity to obtain the following los rate function.

$$L = AP^E \tag{2}$$

where $A = Ak + Dk$ and the precipitation intensity, P, is exponentiated by the nonlinearity parameter E. Note that a simple exponential decay to a constant loss S may be obtained by setting E = 0 and R = 1.

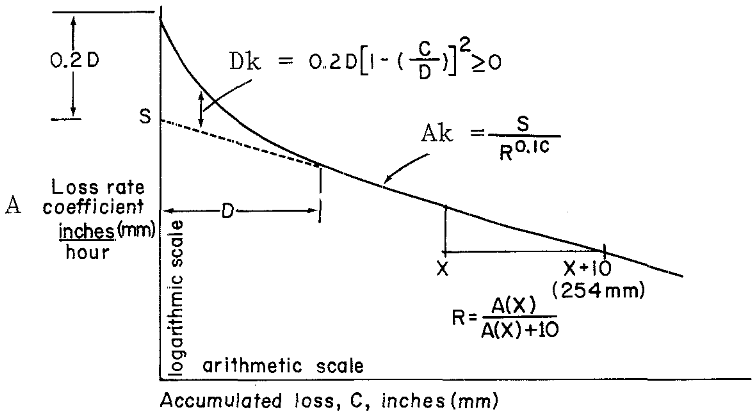

FIG. 1 The HEC exponential loss rate function. *S* is the loss rate for average soil moisture conditions; *D*, initial amount of loss for which the loss rate coefficient is increased to represent antecedent soil moisture conditions; *R*, rate of change of loss rate coefficient as soil moisture increases. (Feldman, 1981)

The HEC exponential loss rate equation is a function of the soil moisture accumulation; however, it is an empirical function whose parameters, S, D, E and R are not readily determined from measurable watershed characteristics. Thus, the function is difficult to apply in ungaged areas where the loss rate parameters must be related to the variable soil types and land covers (geographic characteristics) in a watershed. The parameters are generally obtained using the automated parameter estimation capability of HEC-1. A regional relationship may be developed between the derived parameters and watershed characteristics.

Curve Number Loss Rate Method

The Soil Conservation Service (SCS), U.S. Department of Agriculture, has instituted a soil classification system for use in soil survey maps across the country. Based on experimentation and experience, the agency has been able to relate the drainage characteristics of soil groups to a curve number, CN (SCS, 1972 and 1975). The SCS provides information on relating soil group type to the curve number as a function of soil cover, land use type and antecedent moisture conditions.

Precipitation loss is calculated based on CN and IA (where IA is an initial surface moisture storage capacity in units of depth). CN and IA are related to a total runoff depth for a storm by the standard SCS Method. The SCS method gives total excess for a storm. Thus, incremental excess (the difference between rainfall and precipitation loss) for a time period is computed as the difference between the accumulated excess at the end of the current period and the accumulated excess at the end of the previous period.

The SCS method has been the only method available for estimating loss rates based on the physical characteristics of the catchment. This is of immense practical importance when creating a physically based model in an ungaged watershed. However, the SCS method was developed primarily to evaluate the effect of land use change and not for the simulation of individual events (Rallison and Miller, 1982). In application to individual events the method suffers from theoretical defficiencies (Morel-Seytoux, 1981) and has had some difficulty in reproducing observed events (Rallison and Miller, 1982). To overcome this problem, the method has been developed (Rawls, et al., 1980) for using soil survey information to estimate the parameters of the Greem and Ampt equation. The Hydrologic Engineering Center plans to incorporate this methodology into HEC-1 (as discussed under future plans).

Holtan Loss Rate Method

H. Holtan of the Agricultural Research Service developed a loss rate function (Holtan et al., 1975) which is related to watershed characteristics and also a more sophisticated function of accumulated soil moisture. The Holtan loss rate function has the same general form as the HEC exponential loss rate function but does not consider precipitation intensity; however, the Holtan parameters may be derived directly from the soil water infiltration characteristics of the watershed.

The Holtan infiltration function as implemented in HEC-1 is given by the equation:

$$L = aS^{e} + c \qquad (3)$$

where L is the loss rate in inches per hour; a, is the infiltration capacity in inches per hour per $(\text{inch})^{e}$ of available storage; S is the available storage in inches water equivalent; e, is the exponent of the storage S; and c is the constant rate of infiltration after prolonged wetting in inches per hour.

Because the parameters of this method may be derived from the watershed's physical characteristics, there is potential for including this method in a physically based watershed model (see for example Li et al., 1977). However, as a basis for future investigations, the Green and Ampt equation seems more promising considering the recent efforts made to relate its parameters to readily available soil survey data.

Impervious Areas

An impervious area parameter may be used with any of the loss rate functions. Imperviousness is specified as a percent of the subbasin area. The amount of loss (millimeters or inches) computed in any computation time interval is reduced by the impervious area factor. Thus, 100 percent runoff occurs from that portion of the subbasin that is impervious.

The portion of the rainfall/snowmelt not lost to soil moisture, etc., is referred to as precipitation excess. The next step in the HEC-1 simulation is to convert a hyetograph of rainfall/snowmelt excess into a runoff hydrograph from the subbasin.

Future Plans

The HEC is presently participating in a field investigation in Dry Creek Minnesota (near Jeffers) to determine the efficacy of using remote sensing to determine soil moisture. Data being obtained includes basic hydrometeorologic data; precipitation, wind speed, temperature, streamflow, and soil moisture data. Soil moisture data include point data (gravimetric, neutron probe and microwave) and remotely sensed data by aerial photography (passive microwave, infrared and gamma spectrums).

Among the intended uses for this data is to determine how best to include the various types of soil moisture data collected at different scales (point and remotely sensed measurements) in hydrologic models. Hopefully, inclusion of this data will produce better model predictions. The problem of how to combine soil moisture from various sources has been discussed extensively by Johnson et al. (1982) and the scale at which this data can be used is discussed by Wilkening and Ragan (1982).

Of prime interest to the HEC, is the potential advantage that this new source of soil moisture information has over antecedent precipitation index (API) in determining the initial conditions to be used in an event oriented watershed model, such as HEC-1. To include this information into HEC-1, a physically based and currently popular infiltration method of Green and Ampt (see Mein and Larson (1973)) will be included in HEC-1.

The Green and Ampt method expresses the relationship between cumulative infiltration, F, and infiltration rate, f, as:

$$F = \frac{\psi_f(\phi-\Theta_i)}{(f/_k - 1)} \qquad f>k \qquad (4)$$

where, k is the soil hydraulic conductivity at natural saturation, ψ_f, the average suction at the wetting front, ϕ, total porosity or volumetric water content at saturation and Θ_i, initial water content. This method gives a direct means for including the initial soil moisture condition through the parameters ψ_f and Θ_i.

The major stumbling blocks to this method are in applying the above relationship to actual rainfall amounts and estimation of the parameters of the method. The first stumbling block results because surface ponding must occur for the Green and Ampt equation to be valid. Mein and Larson (1973) for constant rainfall rates and Morel-Seytoux (1981) for variable rainfall rates describe a methodology for calculating a "time to ponding" (the time to ponding is essentially calculated as the time from the beginning of the storm at which the average rainfall intensity is equal to the infiltration rate). After this time, the Green and Ampt equation can be used as long as the rainfall rate exceeds the hydraulic conductivity. Of course, if the rainfall rate becomes less than the hydraulic conductivity then a soil moisture recovery will occur. During major storm events, this is unlikely to be a significant problem.

Parameters of the Green and Ampt equation can be estimated either by calibration or from information available from soil survey data. Rawls et al. (1982) have developed relationships between Green and Ampt parameters and readily available soil survey data. Their results were derived by making an extensive review of published soil water retention curves for different soil texture classes. The Green and Ampt parameters were calculated from the soil water retention relations by first parameterizing these relations with the Brooks and Corey (1964) equation,

$$S_e = \frac{\Theta-\Theta_r}{\phi-\Theta_r} = (\psi b/\psi)^{\lambda} \qquad (5)$$

where S_e equals the effective saturation, Θ_r is the residual water content, ψ_b is the air entry or bubbling pressure and λ is the pore size distribution. Using this relationship and a technique recommended by Morel-Seytoux and Kahnji (1974), the average suction at the wetting front, ψ_f, was calculated. Note that ψ_f is dependent upon the assumed initial water content which in this case is the residual water content.

Table 2 displays the relationship between the Brooks and Corey, Green and Ampt, and soil texture class. Also listed is the variation that is expected in estimates of the Green and Ampt parameters based on texture class. Note that values given for hydraulic conductivity are only representative values and that, according to Rawls et al. (1982), hydraulic conductivity cannot be determined soley on the basis of texture class. These researchers found that greater confidence could be placed in estimates of the Green and Ampt parameters if soil water retention characteristics from a particular soil are known.

TABLE 2. HYDROLOGIC SOIL PROPERTIES CLASSIFIED BY SOIL TEXTURE

Texture class	Sample size	Total porosity (θ) cm³/cm³	Residual saturation (θ_r) cm³/cm³	Effective porosity (θ_e) cm³/cm³	Bubbling pressure (ψ b) Arithmetic cm	Bubbling pressure (ψ b) Geometric † cm	Pore size distribution (λ) Arithmetic	Pore size distribution (λ) Geometric†	Water retained at -0.33 bar tension, cm³/cm³	Water retained at -15 bar tension, cm³/cm³	Saturated Hydraulic Conductivity‡ (K_s) cm/h
Sand	762	0.437[*] (0.374–0.500)	0.020 (0.001–0.039)	0.417 (0.354–0.480)	15.98 (0.24–31.72)	7.26 (1.36–38.74)	0.694 (0.298–1.090)	0.592 (0.334–1.051)	0.091 (0.018–0.164)	0.033 (0.007–0.059)	21.00
Loamy sand	338	0.437 (0.368–0.506)	0.035 (0.003–0.067)	0.401 (0.329–0.473)	20.58 (0.0–45.20)	8.69 (1.80–41.85)	0.553 (0.234–0.872)	0.474 (0.271–0.827)	0.125 (0.060–0.190)	0.055 (0.019–0.091)	6.11
Sandy loam	666	0.453 (0.351–0.555)	0.041 (0.0–0.106)	0.412 (0.283–0.541)	30.20 (0.0–64.01)	14.66 (3.45–62.24)	0.378 (0.140–0.616)	0.322 (0.186–0.558)	0.207 (0.126–0.288)	0.095 (0.031–0.159)	2.59
Loam	383	0.463 (0.375–0.551)	0.027 (0.0–0.074)	0.434 (0.334–0.534)	40.12 (0.0–100.3)	11.15 (1.63–76.40)	0.252 (0.086–0.418)	0.220 (0.137–0.355)	0.270 (0.195–0.345)	0.117 (0.069–0.165)	1.32
Silt loam	1206	0.501 (0.420–0.582)	0.015 (0.0–0.058)	0.486 (0.394–0.578)	50.87 (0.0–109.4)	20.76 (3.58–120.4)	0.234 (0.105–0.363)	0.211 (0.136–0.326)	0.330 (0.258–0.402)	0.133 (0.078–0.188)	0.68
Sandy clay loam	498	0.398 (0.332–0.464)	0.068 (0.0–0.137)	0.330 (0.235–0.425)	59.41 (0.0–123.4)	28.08 (5.57–141.5)	0.319 (0.079–0.559)	0.250 (0.125–0.502)	0.255 (0.186–0.324)	0.148 (0.085–0.211)	0.43
Clay loam	366	0.464 (0.409–0.519)	0.075 (0.0–0.174)	0.390 (0.279–0.501)	56.43 (0.0–124.3)	25.89 (5.80–115.7)	0.242 (0.070–0.414)	0.194 (0.100–0.377)	0.318 (0.250–0.386)	0.197 (0.115–0.279)	0.23
Silty clay loam	689	0.471 (0.418–0.524)	0.040 (0.0–0.118)	0.432 (0.347–0.517)	70.33 (0.0–143.9)	32.56 (6.68–158.7)	0.177 (0.039–0.315)	0.151 (0.090–0.253)	0.366 (0.304–0.428)	0.208 (0.138–0.278)	0.15
Sandy clay	45	0.430 (0.370–0.490)	0.109 (0.0–0.205)	0.321 (0.207–0.435)	79.48 (0.0–179.1)	29.17 (4.96–171.6)	0.223 (0.048–0.398)	0.168 (0.078–0.364)	0.339 (0.245–0.433)	0.239 (0.162–0.316)	0.12
Silty clay	127	0.479 (0.425–0.533)	0.056 (0.0–0.136)	0.423 (0.334–0.512)	76.54 (0.0–159.6)	34.19 (7.04–166.2)	0.150 (0.040–0.260)	0.127 (0.074–0.219)	0.387 (0.332–0.442)	0.250 (0.193–0.307)	0.09
Clay	291	0.475 (0.427–0.523)	0.090 (0.0–0.195)	0.385 (0.269–0.501)	85.60 (0.0–176.1)	37.30 (7.43–187.2)	0.165 (0.037–0.293)	0.131 (0.068–0.253)	0.396 (0.326–0.466)	0.272 (0.208–0.336)	0.06

(Rawls et al., 1982)

* First line is the mean value
Second line is + one standard deviation about the mean
† Antilog of the log mean
‡ Obtained from Fig. 2

Initially this method will be tested on data currently available for small agricultural watersheds. Soil moisture parameters will probably be estimated based on an antecedent precipitation index. As data becomes available from the Dry Creek Project, soil moisture calculated from remotely sensed data will be used directly in the Green and Ampt equation.

LUMPED VERSUS DISTRIBUTED PARAMETER MODELS

HEC-1 calculates hydrologic responses which are average over specified increments of time and space. This is known as a "lumped" representation of the process. The real physical process varies widely in time and space. The lumped models account for spatial variation by allowing the user to specify various sizes of the process components (subbasin and routing reaches). The sizes are chosen (engineering judgment) to obtain the best definition of the runoff which is in keeping with the study objectives and budget. The time increment for the simulation is chosen likewise. Thus, virtually any spatial and temporal definition of the runoff can be obtained.

Work is currently underway at HEC to develop a terrain-based hydrologic model. The terrain is described by a grid of irregular triangular elements which follow slope, soil, land cover, etc., breaks in the watershed. The hydrologic process will be carried out on each of these finite elements. Streamflow will occur along rivlets and streams defined by the slopes/intersectons of the terrain elements.

SUMMARY

The major factors which determine the shape and size of a hydrograph were presented to set the stage for the infiltration process. The HEC-1 methodology for representing that infiltration process was described. Modelers were cautioned not to over emphasize one aspect of the runoff process at the expense of the components before and after it. Finally, the spatial and temporal definition of the runoff process by the models was discussed.

Hydrologic investigations most always result in the analysis of ungaged areas. Analysts are forced to extrapolate the calibrations made on gaged basins to areas where few data are available. The extrapolation process must rely on the hydrologist's ability to relate the parameters of the runoff process to the physical characteristics of the gaged and ungaged basins. In some models when the functions are primarily mathematical fits to the process, this can only be accomplished through the users experience with the model. Other models make use of readily measurable geographic characteristics of a watershed. Their parameters are much more easily transferred from gaged to ungaged areas. Thus, modelers of the hydrologic process should strive to describe that process with functions whose parameters are based on the physical characteristics of the watershed. Those functions must also be based on a sound theory of the physics of the process and still be practical for the intended applications of the model.

REFERENCES

Brakensiek, D.L., 1977, "Estimating the Effective Capillary Pressure in the Green and Ampt Infiltration Equation", Water Resources Research, 13(3), 680.

Corps of Engineers, 1981. HEC-1 Flood Hydrograph Package, Users Manual, Hydrologic Engineering Center, U.S. Army, Davis, California.

Crawford Norman H. and Linsley, Ray K. 1966. Digital Simulation in Hydrology: Stanford Watershed Model IV. Stanford University, Civil Engineering Technical Report No. 39, Palo Alto, California.

Feldman, A.D. 1981. HEC Models for Water Resources System Simulation: Theory and Experience, in Advances in Hydroscience, V.T. Chow ed., Academic Press, New York.

Holtan, H. N., Stitner, G. J., Henson, W. H. and Lopez, N. C. 1975. USDAHL-74 Revised Model of Watershed Hydrology. Technical Bulletin No. 1518, Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C.

Johnson, E.R., Peck, E.L., and Keefer, T.N., 1982, "Combining Remotely Sensed and Other Measurements for Hydrologic Areal Averages", prepared for the National Aeronautics and Space Administration, Greenbelt, Md, NASA-CR-170457.

Li, E.A., Shanholtz, V.D., Contractor, D.N. and Carr, J.C., 1977 "Generating Rainfiall Excess Based on Readily Determinable Soil and Land Use Characteristics", Tran. ASAE, April, pg. 1070.

Linsley, R. K., Kohler, M. A. and Paulhus, J. L. 1975. Hydrology for Engineers, 2nd edition, McGraw-Hill Co., New York.

Mein, R.G., and Larson, C.L., 1973, "Modeling Infiltration During a Study Rain", Water Resources Research, 9(2), pg. 384.

Morel-Seytoux, H.J. and Khanji, J., 1974, "Derivation of an Equaton of Infiltration", Water Resources Research, 10(4), 79.

Morel-Seytoux, H.J., 1981, Engineering Hydrology (ensemble of lecture notes), Hydrologic Program, Colorado State University, 1981.

Neff, E.L., 1977, "How Much Rain Does a Rain Gage Gage?", Journal of Hydrology, 35, pg. 213.

Rallison, R.E. and Miller, N., 1982, "Past, Present and Future SCS Runoff Procedure", from Rainfall-Runoff Relationship, Edited by V.P. Singh, Water Resources Publications, Littleton, Colorado.

Rawls, W.J., Brakensiek, D.L. and Saxton, K.E., 1982, "Estimation of Soil Water Properties", Tran, ASAE, 2515, 1316.

Smith, R.E. 1982, "Rational Models of Infiltration Hydrodynamics", from Modeling Components of Hydrologic Cycle, Edited by V.P. Singh, Water Resources Publications, Littleton, Colorado.

Soil Conservation Service, 1972. National Engineering Handbook, Section 4, U.S. Department of Agriculture, Washington, D.C.

Soil Conservation Service, 1975. Urban Hydrology for Small Watersheds. Technical Release No. 55, U.S. Department of Agriculture, Washington, D.C.

Warwick, A.N., and Neilsen, D.R., 1980, "Spatial Variability of Soil Physical Properties in the Field", from Applications of Soil Physics, ed. D. Hillel, Academic Press, New York.

Wilkening, H.A. and Ragan, R.M., 1982, "A Model for Estimating Time-Variant Rainfall Infiltration as a Fuction of Anticedent Surface Moisture and Hydrologic Soil Type", AgRISTAIRS CP-52-04372, U.S. Department of Agriculture, Agricultural Research Service, Beltsville, MD.

Woodley, W.L., Olsen, A.R., Herndon, A. and Wiggert, V., 1975. Comparison of Gage and Radar Methods of Convective Rain Measurement, Journal of Applied Meteorology, August, p. 909.

Woolhiser, D.A., 1982, "Physically Based Models of Watershed Runoff", from Rainfall-Runoff Relationship, Edited by V.P. Singh, Water Resources Publications, Littleton, Colorado.

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