COMPARISON OF OVERLAND FLOW HYDROGRAPH MODELS

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ABSTRACT: The diffusion equation is a simplification of the two-dimensional continuity and momentum equations. This simpler dynamic model of two-dimensional hydraulics affords the hydrologist a means to quickly estimate floodflow effects for overland flow. A numerical model using the diffusion approach (DHM) is applied to a set of idealized catchments in order to develop synthetic unit hydrograph S-graph equivalents. The model is based on an explicit, integrated finite-difference scheme, and the catchment is represented by topographic elevation and geometric data. Synthetic unit hydrographs (S-graphs) developed from use of the DHM are used to advance interesting relationships between the unit hydrograph lag factor and the constant effective rainfall intensity used to generate the S-graphs. Sensitivity of the synthetic S-graphs to variations in idealized catchment size, slope, shape, friction parameters, and effective rainfall intensity are examined. Comparisons between linear and nonlinear unit hydrograph models, and a diffusion (DHM) and kinematic wave simplification of DHM are made for various time distributions of effective rainfall. Use of the standard SCS unit hydrograph is shown to provide a reasonable approximation of two-dimensional overland flow as predicted by a DHM or kinematic routing technique.

INTRODUCTION

In all hydrologic models, a representation of storm runoff accumulation versus time is used to approximate the arrival of flood flow at a point of concentration. The current trend of hydrologic models to approximate overland flow effects (where collector channel hydraulic effects are negligible) is to use either an idealized overland flow plane with kinematic routing or a unit hydrograph representation. For watershed subareas where overland flow effects dominate the hydrologic/hydraulic response, the question as to whether the kinematic routing overland flow plane concept provides a significant improvement over a standard unit hydrograph approximation is still unanswered in the literature. Of special interest are case studies involving large watershed areas (including tens of square miles of catchment area) where a quasi-physically based (QPB) distributed parameter model is applied in which, for economy purposes, large subareas (in excess of a few dozen acres) are modeled as a single overland flow plane with kinematic routing used to represent the flow tendencies over the flow plane representation. The effect of such subdivision into flow planes or subareas has not been fully evaluated.

The QPB modelers argue that their model is "physically based," whereas a unit hydrograph approach is only a "black box" model. However, as noted by Watt and Kidd (1975), "the choice is then between a 'black box' model and a 'physically based' model which is based on a physical situation quite different than the actual field situation, i.e., a 'black box' model. It would appear, therefore, that whether or not a model has been classified as 'physically based' or 'black box' should carry very little weight in the selection process." Indeed, a physical field test of the overland flow plane representation was provided in the 40-plot instrumented test of Hjelmfelt and Burwell (1984), who concluded that their measurements resulted in a large variability in the runoff quantities between the plots. They note that "one criterion for a valid rainfall-runoff model, in the face of the observed variability, is that it predicts the mean runoff for each event."

Another approach to runoff modeling is to introduce nonlinearity into a unit hydrograph by imposing a variable lag. Hjelmfelt (1984) examined the similarities between the kinematic wave model and a nonlinear unit hydrograph approach, and showed that the Clark unit hydrograph parameters "are descriptive of the approximation process instead of the watershed," and that a variable lag may be used to model nonlinear watershed responses. Such a variable lag or nonlinear unit hydrograph model was used by Reed et al. (1975). Reed et al. also noted "the phenomenon of a shortened lag time for a larger storm."

It is also of interest that in the study by Beven (1979) it was found "that the overall velocities of the flow of water through the network were markedly nonlinear at low to medium discharges but approached a slowly increasing or constant value at high discharges." In Beven's study it is recommended that this upper value of flow velocity be used "as the constant kinematic wave velocity in a linear routing model of the network." In Pilgrim's study (1977), tracings of flood runoff on a 96-acre watershed indicated that the runoff process "is grossly nonlinear at low flows," however, "linearity is approximated at high flows." By comparing the watershed travel time values T to the measured peak discharge Q, Pilgrim developed a relationship of $T = aQ^b$, where a and b are constants. The study notes that "nonlinearity of response is clearly demonstrated, particularly at low flows. However, at medium to high flows the travel times and average velocities become almost constant, indicating that linearity is approximated in this range of flows." Pilgrim concludes that "this explains why the unit hydrograph and other linear synthesis methods often give acceptable results in practical flood estimation, even though the entire flood runoff process is nonlinear."

Because high discharge design storm events are of primary interest to flood protection engineers and planners, the distinction between the use of linear unit hydrograph models, nonlinear unit hydrograph models, kinematic wave QPB, or diffusion routing QPB watershed models becomes less clear. For example, the nonlinearity effects imposed by the QPB kinematic wave model may be argued to violate the true hydrologic response of a watershed subarea (e.g., Beven 1979) during a design storm event. That is, it has not been shown that kinematic wave nonlinearity response represents the catchment nonlinearity.

In this paper, the four modeling approaches discussed here and a variant

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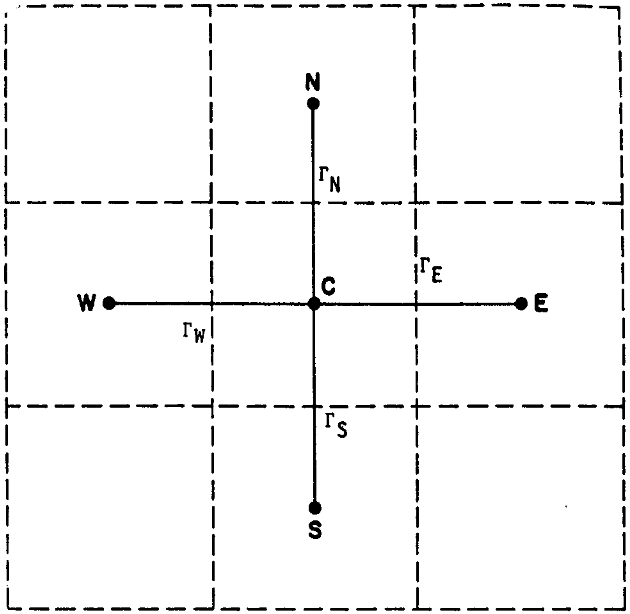


FIG. 1. Two-Dimensional Finite Difference Analog

of the linear and nonlinear unit hydrograph methods based on the standard SCS unit hydrograph (e.g., McCuen 1982) are compared as to the differences in predicted hydrologic response to variable catchment size, slopes, roughness, and the input effective rainfall intensity and temporal pattern. A main objective of this study is the evaluation of models of predicted runoff for catchments dominated by overland flow effects where channelization effects are negligible, and the accumulation of flows with the catchment can be represented by flows over a wide expanse (see Figs. 1 and 2), as is assumed explicitly in the use of the overland flow plane concept.

In other words, in practice, the QPB models often employ large-scale overland flow planes "representative" of a more detailed overland flow plane system interconnected by collector channels. These models typically lump the hydrologic parameters resulting in effective rainfall by a single set of parameters "calibrated" to an assumed set of distributions of rainfalls developed from one (or a few) rain gauges and a single stream gauge record. This QPB modeling approach can be compared to the unit hydrograph modeling approach, which also lumps the hydrologic parameters in producing effective rainfall, but represents the catchment hydraulic response by a linear (or nonlinear) unit hydrograph response function.

Because this paper addresses only the overland flow hydrologic response and comparative approximations from several models, only effective rainfall will be considered throughout the study, thus eliminating the complicating interrelationships possible in the choice of loss function and the subsequent unit hydrograph development from stream gauge data.

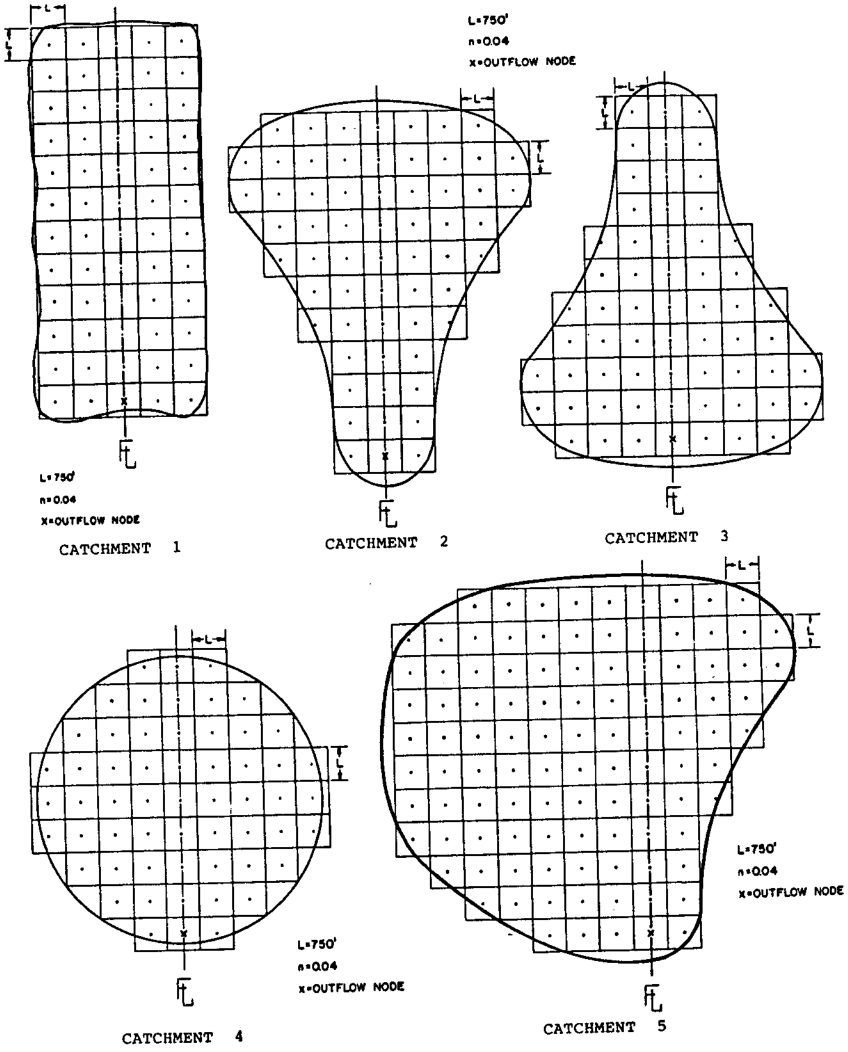


FIG. 2. Discretization of Catchments

HYDROLOGIC MODELS CONSIDERED

When given ample stream gauge data, an averaged S-graph can be developed for use in studying severe storm hydrology. However when stream gauge data is inadequate, synthetic S-graphs are often employed based on hydrologic factors and parameters developed from similar watershed characteristics.

In a previous work, Hromadka and Nestlinger (1985) examined a two-dimensional diffusion model of the complex two-dimensional momentum and continuity equations for the development of synthetic S-graphs. The results of that study indicated that synthetic S-graphs developed from a DHM show a strong correlation to the well-known SCS unit hydrograph S-graph equivalent. Additionally, the DHM approach provides a significant extension to the kinematic routing formulations (typically used in the overland flow submodels of complex hydrologic models) when backwater effects become significant.

The two-dimensional diffusion hydrodynamic model (DHM) of Hromadka et al. (1985) offers a simple and economic means for the estimation of overland flood-flow effects. It can be used to develop a synthetic S-graph using only topographic elevation data and estimates of Manning's friction factor. [An objective of this study is to examine the sensitivity of synthetic S-graphs (developed from overland flow planes) to variations in watershed size, slopes, friction factors, and effective rainfall intensity. From the result it is hoped to identify characteristics of S-graphs which may be generated for direct use in a unit hydrograph model formulation of overland flow effects.]

Also considered are the differences in runoff response due to a time-varying storm pattern using four overland flow runoff hydrograph models: a linear and nonlinear unit hydrograph, a DHM, and a kinematic wave version of the DHM. Comparisons between models to different effective rainfall patterns are made. Additionally, linear and nonlinear unit hydrograph models based on a standard SCS unit hydrograph are used for comparison to the synthetically developed runoff estimates.

MATHEMATICAL DEVELOPMENT FOR TWO-DIMENSIONAL DIFFUSION MODEL

The set of (fully dynamic) two-dimensional unsteady flow equations consists of the equation of continuity

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial H}{\partial t} = 0 \qquad (1)$$

and two equations of motion

$$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_x^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{h}\right) + gh\left(S_{fx} + \frac{\partial H}{\partial x}\right) = 0 \qquad (2)$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q_y^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{q_x q_y}{h}\right) + gh\left(S_{fy} + \frac{\partial H}{\partial y}\right) = 0 \qquad (3)$$

in which q_x and q_y = flow rates per unit width in the x- and y-directions; S_{fx} and S_{fy} = friction slopes in x- and y-directions; H, h, and g = the water-surface elevation, flow depth, and gravitational acceleration, respectively; and x, y, and t are spatial and temporal coordinates. This equation set is based on the assumptions of constant fluid density with zero sources or sinks in the flow field, of hydrostatic pressure distributions, and of relatively uniform bottom slopes.

The local and convective acceleration terms can be grouped together, such that Eqs. 1–3 are rewritten as

$$m_z + \left(S_{fz} + \frac{\partial H}{\partial z}\right) = 0, \qquad z = x, y \qquad (4)$$

where m_z represents the sum of the first three terms in Eqs. 2 and 3 divided by gh. Assuming the friction slope to be approximated by steady flow conditions, Manning's formula in the U.S. customary units can be used to estimate

$$q_z = \frac{1.486}{n} h^{5/3} S_{fz}^{1/2}, \qquad z = x, y \qquad (5)$$

Eq. 5 can be rewritten as

$$q_z = -K_z \frac{\partial H}{\partial z} - K_z m_z, \qquad z = x, y \qquad (6)$$

where

$$K_z = \frac{\dfrac{1.486}{n} h^{5/3}}{\left|\dfrac{\partial H}{\partial S} + m_S\right|^{1/2}}, \qquad z = x, y \qquad (7)$$

The symbol S indicates the flow direction which makes an angle of $\theta = \tan^{-1}(q_y/q_x)$ in the positive x-direction.

Values of m are assumed negligible by several investigators (Akan and Yen 1981; Xanthopoulos and Koutitas 1976), resulting in the simple diffusion model:

$$q_z = -K_z \frac{\partial H}{\partial z}, \qquad z = x, y \qquad (8)$$

The proposed two-dimensional flood flow model is formulated by substituting Eq. 8 into Eq. 1:

$$\frac{\partial}{\partial x} K_x \frac{\partial H}{\partial x} + \frac{\partial}{\partial y} K_y \frac{\partial H}{\partial y} = \frac{\partial H}{\partial t} \qquad (9)$$

NUMERICAL MODEL FORMULATION (GRID ELEMENTS)

For uniform grid elements, the integrated finite difference version of the nodal domain integration (NDI) method is used. For grid elements, the NDI nodal equation is based on the usual nodal system shown in Fig. 1. Flow rates along the boundary Γ are estimated using a linear trial function assumption between nodal points.

For a square grid of width δ:

$$q\big|_{\Gamma_E} = -\frac{\left(K_x\big|_{\Gamma_E}\right)(H_E - H_C)}{\delta} \qquad (10)$$

where

$$K_x\Big|_{\Gamma_E} = \begin{cases} \dfrac{\left(\dfrac{1.486}{n}\, h^{5/3}\right)\Big|_{\Gamma_E}}{\left|\dfrac{H_E - H_C}{\delta \cos \theta}\right|^{1/2}}; & \bar{h} > 0 \\ 0; & \bar{h} \leq 0 \quad \text{or} \quad |H_E - H_C| < 10^{-3} \end{cases} \tag{11}$$

In Eq. 11, h and n are both the average of the values of C and E, i.e., $h = (h_C + h_E)/2$, and $n = (n_C + n_E)/2$. Additionally, the denominator of K_x is checked such that K_x is set to zero if $| H_E - H_C |$ is less than a tolerance such as 10^{-3} ft.

The model advances in time by an explicit approach

$$\mathbf{H}^{i+1} = \mathbf{K}^i \mathbf{H}^i \quad \ldots\ldots \tag{12}$$

where the assumed input flood flows are added to the specified input nodes at each timestep. After each timestep, the hydraulic conduction parameters of Eq. 11 are reevaluated, and the solution of Eq. 12 reinitiated. The timestep is allowed to increase as long as the magnitude of change of a nodal point flow depth is less than a specified tolerance (e.g., 0.1 ft). Should a nodal point flow-depth variation exceed the tolerance, then the last estimates of $\mathbf{H}^{i+1}$ are rejected, the timestep is halved, and the last application of Eq. 12 is repeated. Using a variable timestep size allows for a considerable savings in computational effort while preserving a level of computational accuracy. Verification of the two-dimensional hydrodynamic model is given in Hromadka et al. (1985) for the class of problems involving severe peaked flood hydrographs, such as those resulting from dam breaks.

TEST CATCHMENT GEOMETRIES

Five test catchments are considered in this study. Catchments 1–4 are all symmetrical about the flowline (see Fig. 2), where flows approach the flowline and then travel to the downstream point of concentration. Catchment 5 [Fig. 2(*e*)] is nonsymmetrical, and is considered to investigate the sensitivity of synthesized results to symmetry in the area. The overland flow is modeled by use of the DHM, using a uniform constant value for Manning's friction factor. Additionally, nodal elevations are also held constant so that as the grid size is increased, the effects are a corresponding increase in the catchment area and a decrease in the cross slope and the slope of the flowline. All catchments have uniform cross slope to the flowline of 0.80%, with a flowline slope of 0.40% corresponding to a grid dimension of 750 ft. For larger grid sizes, all slopes decrease proportionately. Runoff flows toward the flowline, and then toward the point of concentration. Consequently, the flowline grid elements serve as a wide rectangular channel of a width equal to the grid dimension and, therefore, the "collector" channel hydraulics is also being represented by the overland flow plane hydraulics for both the kinematic wave and diffusion routing models. That is, the flowline grid elements can be interpreted as a

representative overland flow strip (of unit width equal to a grid width), where the tributary catchment contributes runoff according to the response determined by their respective overland flow hydraulics. This type of representation may be used for wide alluvial fan-type catchments where flood flows are of a wide expanse and of relatively small depth, and yet the alluvial fan is criss-crossed by smaller shallow-depth collector channels.

SYNTHETIC S-GRAPH DEVELOPMENT

The instantaneous unit hydrograph (IUH) can be represented in S-graph form. S-graphs are developed for each of the catchments by distributing a uniform constant effective rainfall rate to a catchment and noting the runoff hydrograph. By dividing the ordinates of the runoff hydrograph by the maximum flowrate (i.e., the equilibrium flowrate), the ordinates of all S-graphs can be represented in terms of percentage of ultimate discharge. Lag is defined herein as the time from the beginning of effective rainfall to 50% of ultimate discharge; all S-graphs can be dimensionalized with respect to time. Hence, all S-graphs must reach 50% of ultimate discharge at 100% lag using the definitions given here.

Sensitivity of DHM S-Graph to Effective Rainfall Intensity

For each catchment, S-graphs were developed corresponding to constant effective rainfall intensities of 0.1, 0.5, 1.0, 2.0, and 3.0 in./hr. Each S-graph varied depending on the effective rainfall intensity used (for example, see Fig. 3). However when normalized with respect to ultimate discharge and lag, the S-graphs became nearly coincident, indicating that the dominating parameter in the IUH development for a given catchment from the DHM technique is the watershed lag value. This indicates a relative consistency in S-graph shape as developed by the DHM model.

Sensitivity of DHM S-Graph to Watershed Area and Slope

As discussed earlier, the DHM nodal elevations are held constant and, as the grid size increased, not only does the catchment area increase, but the slopes all decrease. Consequently, a wide range of catchment behavior is being investigated by varying the DHM grid size.

To investigate the sensitivity of the synthetic S-graph development to watershed area and corresponding slopes, S-graphs were developed for each catchment using grid sizes of 100, 200, 500, 750, 1,500, and 3,000 ft. For the 60-grid DHM schematic, this corresponds to overland flow drainage areas of between 13 acres and over 19 sq miles. A constant effective rainfall intensity of 1 in./hr was used for this set of tests. As shown in Fig. 4(*a*), the synthetic S-graph development was again producing nearly identical S-graphs, but of course watershed lag differed depending on the watershed area and slope. Only Catchment 5 is considered in Fig. 4(*a*) (and later figures), which shows the maximum variation of the 5 catchments studied. To isolate the effects of variable crossfall gradients of the overland flow plane, the 750-ft grid model of Catchment 5 is studied for the case of a flowline gradient slope of 0.0040 (0.40%), a friction factor of 0.040, and various crossfalls. The results of Fig. 4(*b*) show a negligible variation in the synthetic S-graphs produced from a constant rainfall intensity of 1 in./hr.

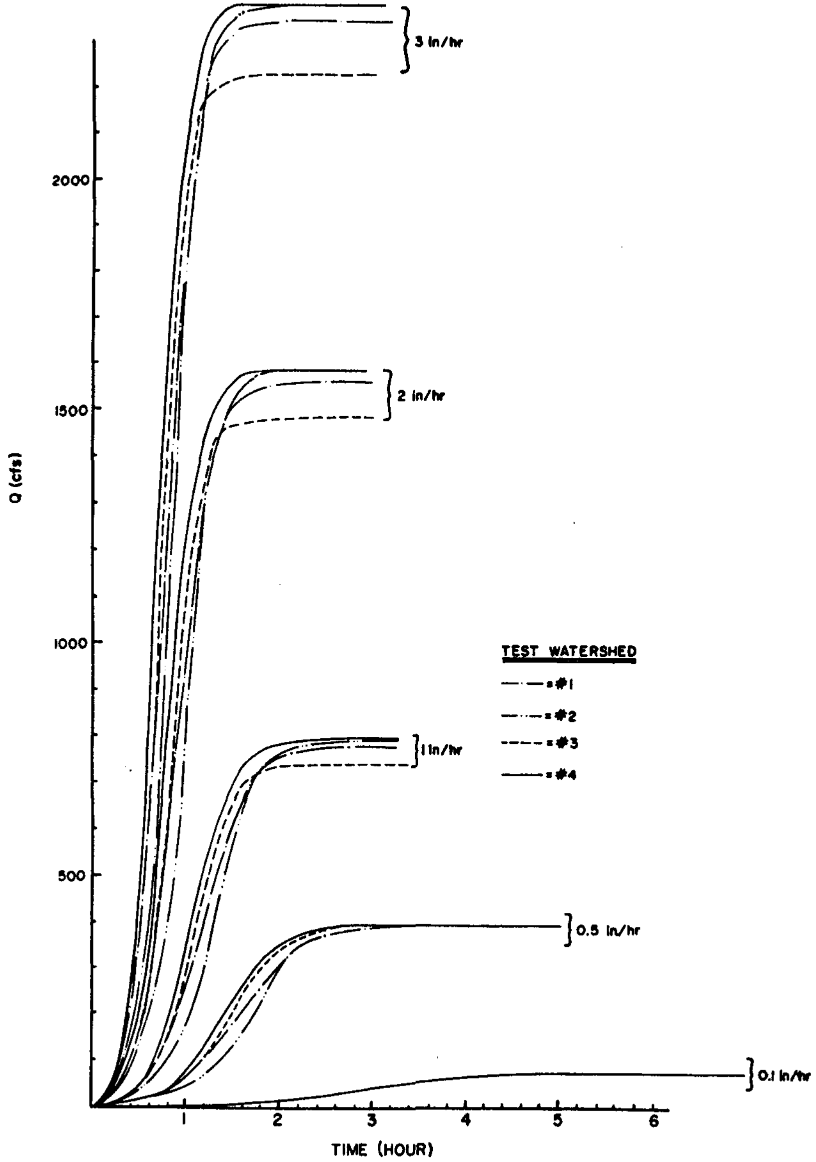


FIG. 3. Synthetic S-Graph Development for Various Effective Rainfall Intensities

Sensitivity of DHM S-Graph to Manning's Friction Factor

By varying the Manning's friction factor, and using a constant effective rainfall rate of 1 in./hr, it was found that again the S-graph development was nearly identical (Fig. 5), but the watershed lag varied depending upon the friction factor used.

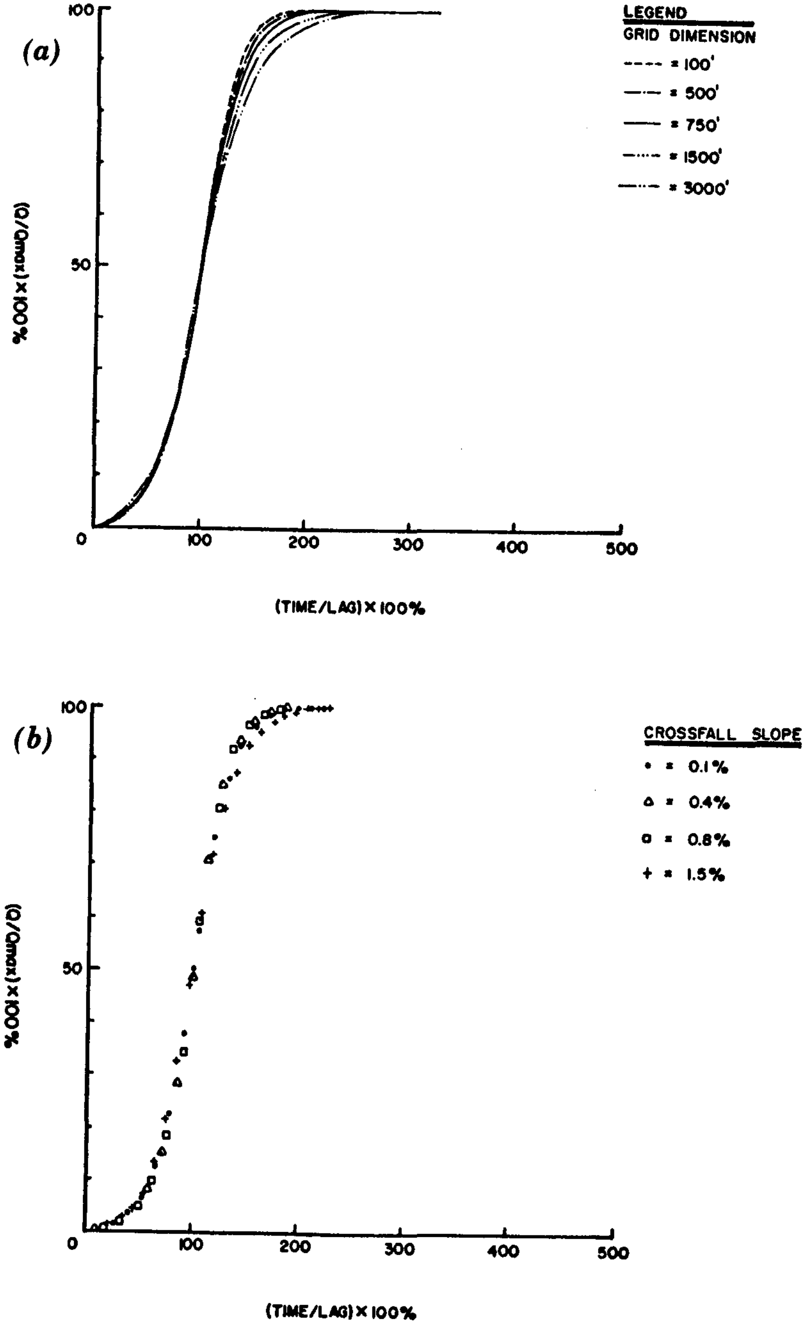


FIG. 4. Synthetic S-Graph for Catchment 5: (*a*) 1 in./hr Effective Rainfall; (*b*) for Various Crossfalls (750-ft Grids)

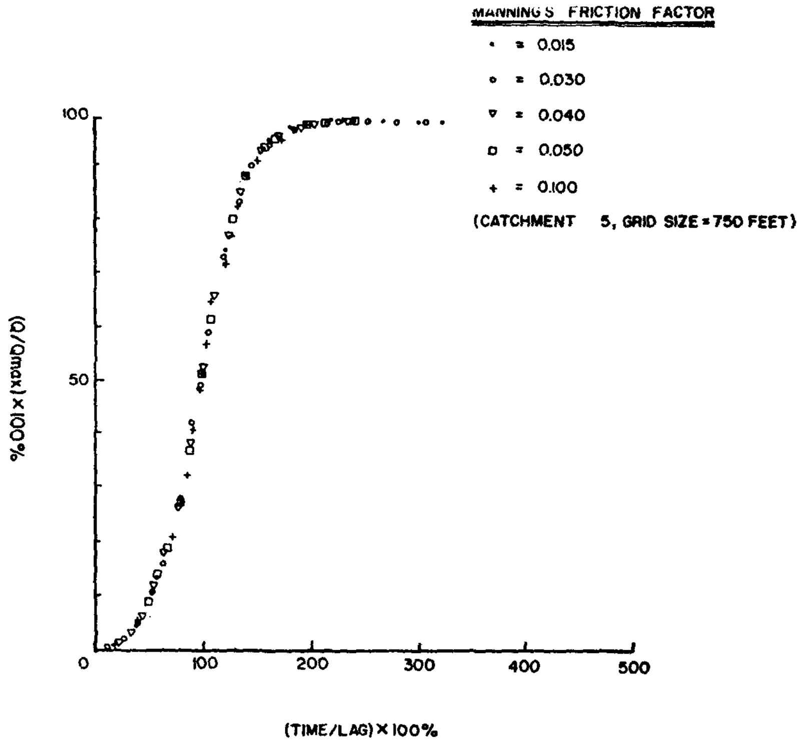


FIG. 5. Variation in Synthetic S-Graphs with Variation in Manning's Friction Factor (1 in./hr) Effective Rainfall

Sensitivity of DHM S-Graph to Catchment Shape

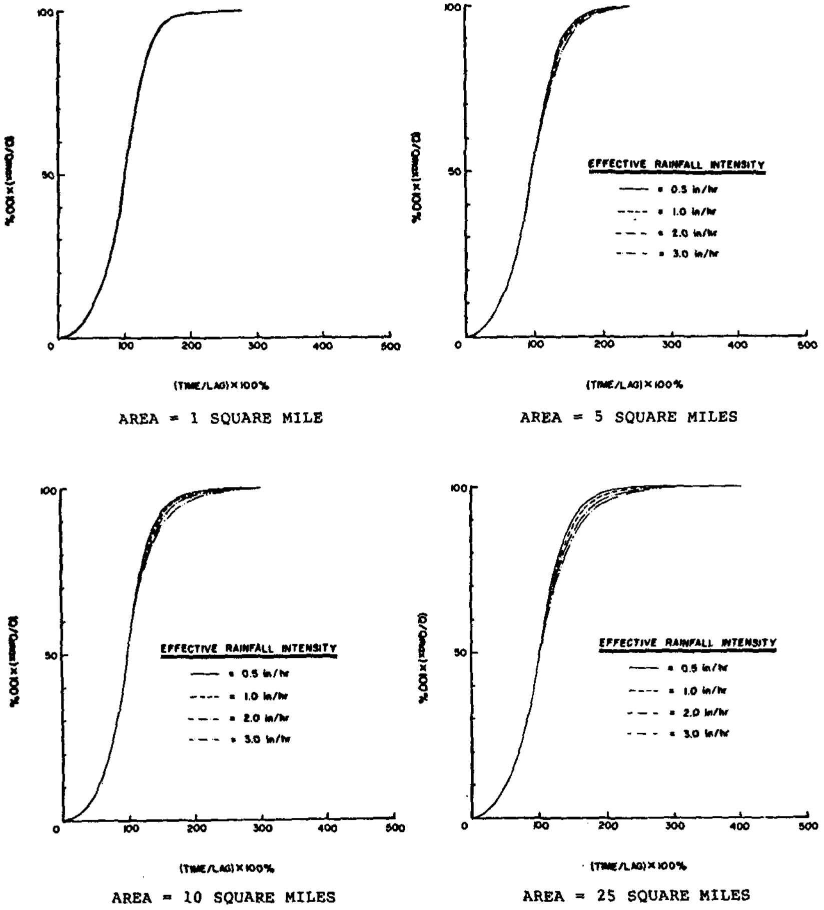
By comparing the various S-graph test results it is evident that the DHM-produced S-graphs for the five test catchments are relatively insensitive to constant effective rainfall intensity, watershed area and slope, and the Manning's friction factor. It can also be shown that the S-graphs vary only slightly with a combination of changing rainfall intensity and catchment area (Fig. 6) and, consequently, an ordinate-average S-graph can be developed for each catchment shape. A comparison of these averaged S-graphs is given in Fig. 7, which shows only a minor variation due to catchment shape for the shapes considered.

Relating Lag to Effective Rainfall Intensity

With the above test results, a relationship between the catchment lag and constant effective rainfall intensity used to develop the synthetic S-graph becomes apparent; namely, the lag decreases with increasing constant effective rainfall intensity. More precisely, the DHM-estimated lag and the constant effective rainfall intensity i are related by (see Fig. 8):

$$\text{lag}(i) = k_1 i^{k_2} \quad \text{(13)}$$

where, for a particular watershed, k_1 and k_2 are constants. For example, from Fig. 8, $k_2 = -0.40$ for each of the test watersheds. Eq. 13 is of a form similar to the relationship developed by Pilgrim (1977) relating catchment travel time to peak flow.



AREA = 1 SQUARE MILE

AREA = 5 SQUARE MILES

AREA = 10 SQUARE MILES

AREA = 25 SQUARE MILES

FIG. 6. Catchment 5 (Effective Rainfall = 0.5–3.0 in./hr)

From the lag(i) relationship it is noted that:

1. Catchment lag decreases with increasing magnitude of effective rainfall intensity [this shows agreement with Reed et al. (1975)].
2. At low effective rainfall intensities, the variation in lag values is high; consequently, the catchment would be expected to respond as a highly nonlinear system for low-frequency storm events [this agrees with Pilgrim (1977)].
3. At high effective rainfall intensities, the variation in lag values is low; consequently, the catchment would respond more as a linear system for severe storm events [this agrees with Pilgrim (1977) and Reed et al. (1975)].

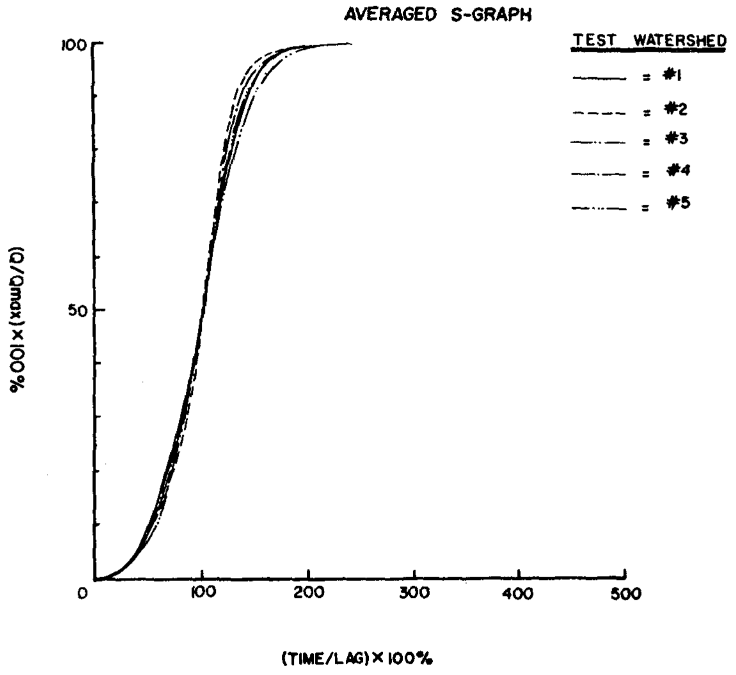


FIG. 7. Average S-Graph

These observations, developed from the application of the DHM approach to idealized catchments, indicates that the unit hydrograph approach may be appropriate for the modeling of overland flow response during high intensity effective rainfalls which are of interest for urban watershed flood control systems.

Kinematic Wave Hydrodynamic Model

The two-dimensional DHM formulation of Eq. 8 can be simplified into a kinematic wave approximation of the two-dimensional equations of motion by using the slope of the topographic surface rather than the slope of the water surface as the friction slope in Eq. 5. That is, flowrates are driven by Manning's equation, and backwater effects, reverse flows, and ponding effects are entirely ignored.

As for the diffusion model, an S-graph is developed for the kinematic wave model by using a constant effective rainfall rate distributed over the watershed. The resulting S-graphs are shown in Fig. 9 for the case of watershed Catchment 5. Again, all S-graphs are similar when normalized with respect to watershed lag. A lag versus intensity relationship is found to be similar to that developed from the DHM formulation. Consequently, for the overland flow catchment geometries considered, the kinematic and diffusion hydrodynamic models would give similar results when flows are all free-draining; that is, when backwater effects are negligible.

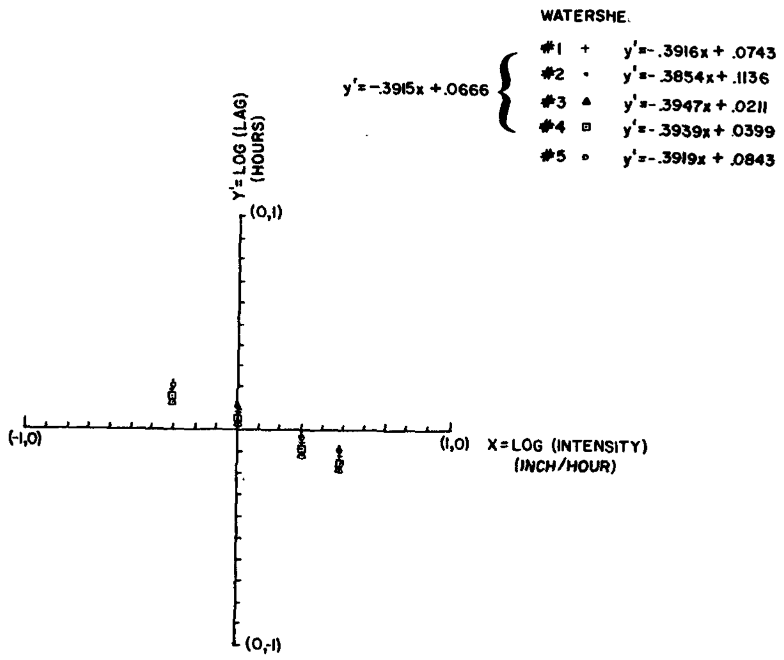


FIG. 8. Lag versus Effective Rainfall Intensity (*i*) Correlation

Time-Varying Effective Rainfall Effects

Four models are considered as to the prediction of overland flow response when a time-varying effective rainfall is distributed over the watershed: (1) DHM; (2) kinematic wave version of the DHM; (3) unit hydrograph; and (4) nonlinear unit hydrograph. The DHM and kinematic wave were described previously. The unit hydrograph model is based on the catchment S-graph, using a lag "representative" of the storm's effective rainfall intensity. The representative lag value is based on the developed lag versus effective rainfall relationship, using the effective rainfall corresponding to 90% of the maximum effective storm rainfall. This value was arbitrarily chosen based on the several tests in attempts to correlate the timing of the resulting runoff hydrograph to the timing developed using the DHM results.

The nonlinear unit hydrograph model varied the unit hydrograph for each unit effective rainfall based on the lag versus effective rainfall intensity, Consequently, each unit hydrograph lag varied according to a fixed relationship between catchment S-graphs developed from various storms of constant effective rainfall.

For this set of tests, Catchment 1 (area ≈ 700 acres) was subjected to three patterns of effective rainfalls (storms A, B, and C). These storms provided equal volumes of runoff, distributed over 3 hrs of storm time, with the peak effective rainfall intensity (i) of 2 in./hr occurring at 0.5, 1.5, and 2.5 hrs, respectively.

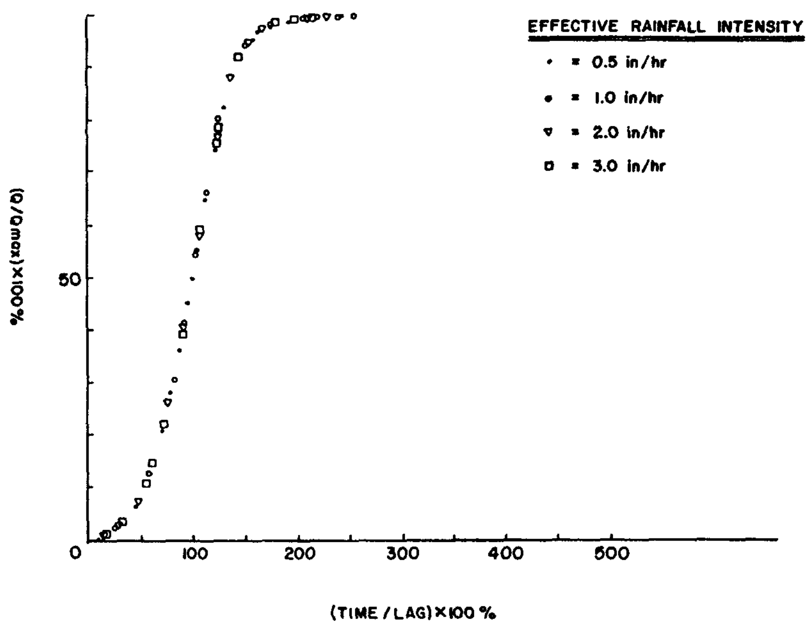


FIG. 9. Kinematic Wave Model Generated Synthetic S-Graph (Catchment 5)

Fig. 10 shows the resulting runoff hydrographs for the three storm patterns, using each of the four methods. From the figures it is noted that:

1. The diffusion and kinematic wave models give similar results.
2. The linear and nonlinear unit hydrograph models give different results, mostly in peak flowrate estimates, depending on the storm pattern (the unit hydrographs were developed from the synthetic S-graphs from the previous DHM results).
3. The DHM (and kinematic), linear, and nonlinear models all differ in estimated watershed response of both peak flowrate and hydrograph timing.

To further investigate the differences in overland flow modeling predictions, Catchment 1 was modified to have cross slopes of 0.20%, and a longitudinal slope of 0.40%. The resulting runoff hydrographs for the three storm patterns and six methods were computed. Fig. 11 shows one set of the hydrographs for the second storm pattern. Again, differences in model predictions are consistent as to the steeper-sloped catchment tests. However, the kinematic wave and diffusion formulations are indicating some deviation in predicted results.

A final test of the diffusion and kinematic wave formulations is shown in Fig. 12, where the friction factors are increased significantly. The two methods again show nearly identical results in predicting overland flow response.

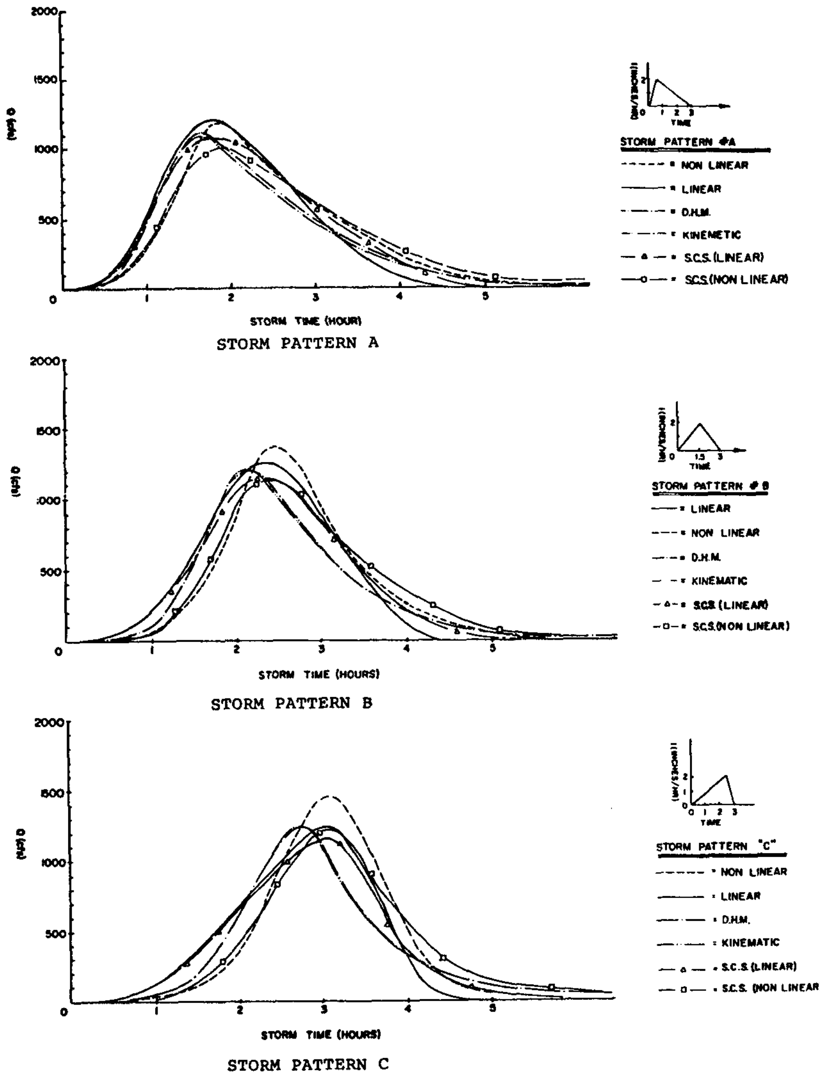


FIG. 10. Storm Pattern Runoff Hydrographs (Catchment 1)

SCS Unit Hydrograph

The U. S. Department of Agriculture Soil Conservation Service uses a unit hydrograph generalized from stream gauge data (McCuen 1982). This unit hydrograph can also be used as another comparison to the previous modeling results.

For comparison purposes, both the linear and nonlinear unit hydrograph models (using the SCS unit hydrograph) were used to model the three storm patterns (types A, B, and C). The resulting runoff hydrographs are

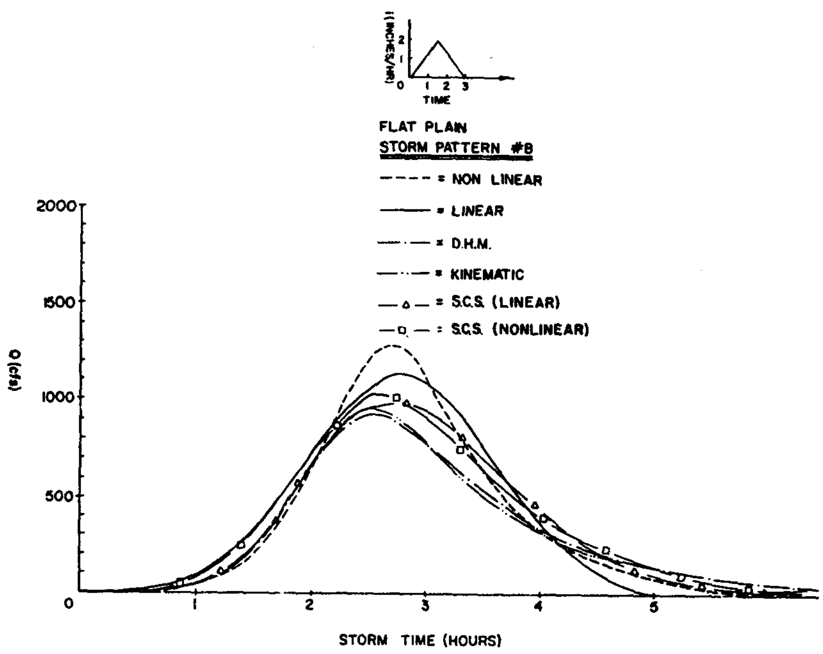


FIG. 11. Flat Plain Runoff Hydrographs: Storm Pattern B

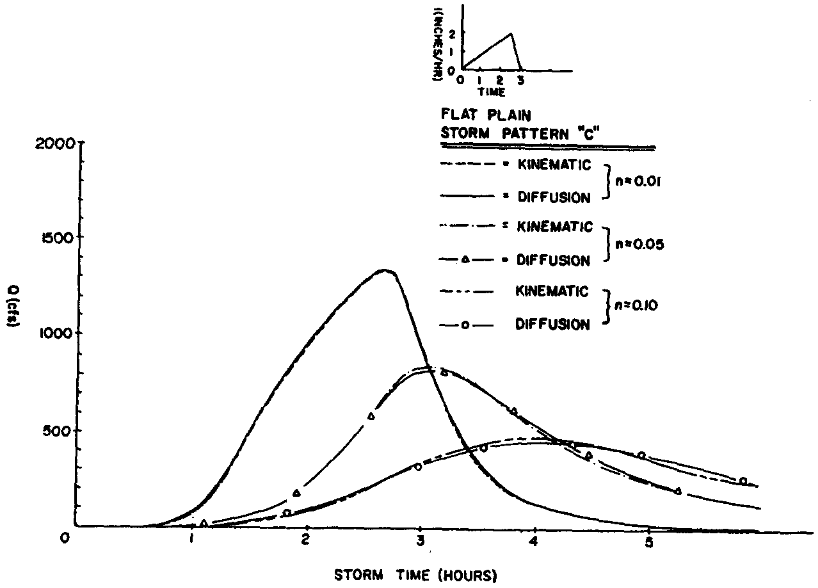


FIG. 12. Comparison of Kinematic and Diffusion Routing Techniques

included in Figs. 10 and 11. From these comparisons it was seen that use of the SCS unit hydrograph more closely approximates the runoff response from the DHM or kinematic routing models than when using unit hydrographs developed from the actual DHM application.

The nonlinear unit hydrograph model (SCS unit hydrograph) more closely matched the DHM results for the front- and central-loaded design storm than the linear unit hydrograph model; however, both unit hydrograph models showed equivalent timing results for the rear-loaded design storm.

CONCLUSIONS

From the results of this study, several conclusions are advanced, as follows:

1. The diffusion and kinematic wave versions of the DHM produce similar overland flow runoff responses when backwater effects are negligible.
2. Watershed lag is related to effective rainfall intensity (i) by lag(i) = $k_1 i^{k2}$, where k_1 and k_2 are constants.
3. As the storm's effective rainfall intensity increases, watershed lag decreases.
4. For high effective rainfall intensity storms, the lag varies considerably less than during a low effective rainfall intensity storm; consequently, during severe storms of high intensity, the linear unit hydrograph may apply as a reasonable approximation.
5. The DHM, linear, and nonlinear unit hydrograph models differ in runoff hydrograph predictions of overland flow hydraulics.
6. Use of the standard SCS unit hydrograph in a linear or nonlinear unit hydrograph model provides a reasonable approximation of the catchment response developed from the DHM and kinematic routing models.

FUTURE WORK

Several questions have arisen during the course of this study which focus upon the linear versus nonlinear assumptions that are still debated in the hydrologic literature. Essentially, the question as to whether "sheetflow" hydraulics applies to the hydrologic scale overland flow plane model remains unanswered.

In a future paper, the overland flow plane will be reevaluated as to watershed response when randomly imposed systems of collector channels are superimposed. In this fashion, a more realistic hydraulic model of the field condition is represented.

APPENDIX. REFERENCES

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