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SIMPLIFICATIONS OF WATERSHED GEOMETRY AFFECTING SIMULATION OF SURFACE RUNOFF*[1]

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ABSTRACT

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In formulating the equations describing the flow of water on the surface of a watershed, geometric simplifications must be made. A geometric simplification is the substitution of a simple geometry for a more complex one. The problem is to examine techniques for and consequences of such simplifications, and thereby develop objective procedures for geometric simplification of complex watersheds.

Watershed geometry is represented by a series of planes and channels in cascade. When overland flow and open-channel flow in the cascade are described by the kinematic wave equations, the resulting mathematical model is called the kinematic cascade model. Planes are fitted to coordinate data from topographic maps by a least-squares procedure. Residuals of this fit form a geometric goodness-of-fit statistic as the improvement over using the mean elevation. Channel elements are determined, using Gray's method, as the slope of the hypotenuse of a right triangle with the same area as that under the observed stream profile. The ratio of the altitude of this right triangle to the total relief of a stream is the index of concavity, a channel goodness-of-fit statistic. An overall goodness-of-fit statistic is the drainage density ratio, the ratio of drainage density in the cascade of planes and channels to drainage density of the watershed.

The mean value of a hydrograph goodness-of-fit statistic, as the improvement over using the mean discharge, increases as the geometric goodness-of-fit statistic increases but also decreases as the drainage density increases. A combined goodness-of-fit statistic, the product of the drainage density ratio and the geometric goodness-of-fit statistic, is related to the degree of distortion in optimal-hydraulic roughness parameters. Distortions in watershed geometry result in optimal roughness parameters smaller than the corresponding empirically derived values for simple watersheds where less distortion is involved.

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Given rainfall, runoff and topographic data for a small watershed, it is possible to define the simplest kinematic cascade geometry which when used in simulation will, on the average, preserve selected hydrograph characteristics to a given degree of accuracy.

INTRODUCTION

The problem

As used here, the term watershed means an area above a specified point on a stream enclosed by a perimeter. The watershed perimeter defines an area where surface runoff will move into the stream or its tributaries above the specified point. Thus the term watershed connotes a physical entity for which continuity statements can be made. If attention is limited to stream channels and they are conceptualized as single lines, then the resulting line diagram is called a channel network. A simple concept of the surface of a watershed is that it consists of the channel network and the inter-channel areas of overland flow within the watershed perimeter. Flow from this surface is called surface runoff.

In formulating the equations describing the flow of water on a watershed surface, geometric simplifications must be made. Geometric simplification is the substitution of a rather simple geometry for a more complex one. The problem is to examine techniques for, and consequences of, such simplifications, and thereby develop objective procedures for geometric simplification of complex watersheds.

Background

Kinematic wave theory via the kinematic cascade model discussed below is the basic tool used here for surface runoff simulation. Under conditions where the momentum equation can be approximated to a good degree by maintaining only terms expressing bottom slope and friction slope, the flow is called kinematic. Under these conditions, local depth and discharge on a plane have a simple functional relation:

$$Q = \alpha h^n \tag{1}$$

where
Q = local discharge
h = local depth
α = coefficient incorporating slope and roughness
n = exponent reflecting flow type, namely, laminar or turbulent

These definitions are for flow over a hydraulically smooth plane. However, the same form can be used for irregular surfaces where the mean flux per unit width is proportional to the storage in an incremental area. An early reference (Lighthill and Whitham, 1955) gives the theory of kinematic waves

(waves under conditions discussed above). From this theoretical treatment, the next step is to sources developing the kinematic cascade as a hydrologic model.

Henderson and Wooding (1964) applied the theory to flow over a plane and compared their results to data with a good reproduction of the observations. The next step, extending the theory to a watershed model, was made by Wooding [see Wooding (1965a, b, 1966)] who stated the theory, discussed numerical solutions and compared his results with observed runoff data. This extension was an important step in developing a general watershed model based upon kinematic flow. A complex watershed was modeled as two symmetric lateral planes contributing to a channel bisecting the area. Schematically, the model could be likened to an open book with the channel in the center so that there is a lateral slope for the planes but also a down channel slope for the channel and planes. This model will be referred to as Wooding's model.

The essential step from Wooding's model to the kinematic cascade model was made by Brakensiek (1967). This step is fundamental in that instead of a single plane discharging into a channel — a lumped nonlinear model — Brakensiek broke the lateral flow portion into a sequential series (cascade) of planes. With this cascade formulation an obvious extension is to let each plane have its own characteristics resulting in a distributed model. Kibler and Woolhiser (1970, p. vii) defined a kinematic cascade as follows:

> A kinematic cascade is defined as a sequence of n discrete overland flow planes or channel segments in which the kinematic wave equations are used to describe the unsteady flow. Each plane or channel is characterized by a length, l_k, width, w_k, and a roughness-slope factor, α_k.

Thus, the kinematic cascade is a distributed (in that each element may have different characteristics, including rainfall excess) model with lumped parameters in the subelements. The model is a nonlinear model since values for n in eq.1 are generally not equal to 1. For examples of recent applications in urban and rural agricultural watersheds, see Harley et al. (1970) and Singh (1974).

Scope and objectives

The emphasis of the work reported here is on rainfall excess—surface runoff relationships on small natural or cultivated agricultural watersheds with drainage areas of less than a few square kilometers. The problems in assuming uniform input patterns are recognized but by considering only small watersheds, these problems are presumably minimized.

Our principal objective was to develop objective procedures for geometric simplification of small watersheds and specifically to relate statistics of the simplified geometry to watershed and hydrograph characteristics.

Hobson's procedure as modified

A topographic map, among other things, defines a watershed perimeter and channel network. Moreover, each point on and within the perimeter is defined by coordinates (x,y,z). Similar to Hobson's (1967) notation, but in correct matrix form, e_i is an elevation point corresponding to (u_i,v_i) as the associated x and y coordinates. The coefficients of the least-squares-fitted plane are b_i. With this notation:

$$E = [UV]B \tag{2}$$

defines the elevation vector where:

$$B = [UV]^{-1}E \tag{3}$$

with

$$B = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \tag{4}$$

as the coefficient vector:

$$E = \begin{bmatrix} \Sigma e_i \\ \Sigma u_i e_i \\ \Sigma v_i e_i \end{bmatrix} \tag{5}$$

as the elevation vector, and:

$$[UV] = \begin{bmatrix} N \Sigma u_i \Sigma v_i \\ \Sigma u_i \Sigma u_i^2 \Sigma u_i v_i \\ \Sigma v_i \Sigma u_i v_i \Sigma v_i^2 \end{bmatrix} \tag{6}$$

With this notation, a computed elevation value is:

$$\hat{z}_i = b_1 + (b_2 x_i + b_3 y_i) \tag{7}$$

Deviations from observed elevation values are of the form $z_i - \hat{z}_i$ where z_i is an observed elevation, and $\hat{z}_i$ is given by eq.7. If a mean elevation is computed as:

$$\bar{h} = \sum_{i=1}^{N} z_i/N \tag{8}$$

then the sum of squares about this mean is:

$$S_1^2 = \sum_{i=1}^{N} (z_i - \bar{h})^2 \tag{9}$$

where N is the number of data points. The sum of squared deviations or residuals is:

$$S_2^2 = \sum_{i=1}^{N} (z_i - \hat{z}_i)^2 \tag{10}$$

where $\hat{z}_i$ is computed using eq.7. A geometric goodness-of-fit statistic (Lane, 1975) is:

$$R_P^2 = (S_1^2 - S_2^2)/S_1^2 \tag{11}$$

as the relative improvement, by fitting the plane, over using the mean elevation.

The procedure for fitting a cascade of planes and channels to watershed data from topographic maps is described below. First, coordinate data over the watershed area are selected so that each point represents nearly the same area within the perimeter. A single plane fit to the coordinate data is the simplest "cascade". The next cascade would be one channel and two lateral planes — Wooding's model. More complex models are developed by including successively more planes and channels in the cascade. Throughout the procedure, certain watershed properties are preserved. Each of the successively more complex models has the same total drainage area. If the length of the main channel, L_c, is also preserved, then the area and length specify the width for a single plane. For Wooding's model, the main channel length is set equal to L_c and, thus, the width of the lateral planes is specified. As the complexity of the kinematic cascade increases, the freedom in choosing the arrangement and size of the elements also increases.

Gray's procedure as modified

Gray (1961) defined slope of the main stream, S_c, as the slope of a line drawn along the measured profile which has the same area under it as is under the observed profile. This slope is the slope of the hypotenuse of a right triangle with the same area, A, and length, L_c, as the observed profile. With respect to the triangle, the area is:

$$A = \tfrac{1}{2} L_c h \tag{12}$$

and the slope is:

$$S_c = h/L_c \tag{13}$$

If eq.12 is solved for h and this is substituted into eq.13, then:

$$S_c = 2A/L_c^2 \tag{14}$$

as the equivalent channel slope. With respect to the observed stream profile:

$$A = \int_{y=0}^{H_c} (L_c - x)\mathrm{d}y \tag{15}$$

where x is distance along the channel profile, y is elevation above the assumed base level, H_c is the elevation of the highest point in the main channel above the assumed base level, and if the slope is $S(x)$, then:

$$\mathrm{d}y = S(x)\mathrm{d}x \tag{16}$$

in eq.15.

With this value of dy, eq.15 becomes:

$$A = \int_0^{L_c} (L_c - x)S(x)\mathrm{d}x \tag{17}$$

and eq.14 becomes:

$$S_c = 2\int_0^{L_c} \frac{(L_c - x)}{L_c^2} S(x)\mathrm{d}x \tag{18}$$

where $(L_c - x/)L_c^2$ can be considered a weighting factor. For example, this factor is zero at $x = L_c$ and maximum at $x = 0$. Therefore, Gray's method produces a channel slope weighted by distance from the headwaters of the main stream. The highest weight is given to the slope at the outlet.

If H_c is the total relief of the stream and h is the altitude of the above right triangle, then their ratio, h/H_c, can be used as an overall index of stream concavity so that a value less than 1 (the usual case) corresponds to an overall concave profile, while a value greater than 1 indicates an overall convex profile. This index is used as a measure of how well the channel slope is represented by a straight line.

Drainage density ratio

Assume that a given watershed with drainage density, D_d, is modeled as a simplified cascade of planes and channels with drainage density, d_d. The ratio d_d/D_d is between 0 and 1 and is a measure of how well the channel network is modeled with respect to total length. This ratio and the index of concavity provide measures of the goodness-of-fit of the model's channels with respect to the linear dimensions of the channels in the watershed (prototype).

Kinematic cascade model

In kinematic wave theory the continuity equation is:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = q(x,t) \tag{19}$$

with the stage—discharge equation defined in eq.1 as:

$$Q = \alpha h^n \tag{20}$$

where
h = local depth of flow
u = local mean velocity
t = time
x = distance in direction of flow
q = lateral inflow
Q = discharge rate
α = coefficient
n = exponent (3.0 for laminar flow and 1.5 for turbulent flow)

The kinematic cascade model consists of the above equations and boundary conditions appropriate for the cascade of planes and channels. Kibler and Woolhiser (1970) presented a finite-difference method of solution known as the single-step Lax-Wendroff method. This method from Houghton and Kasahara (1968) was compared with two other finite-difference schemes by Kibler and Woolhiser (1970). Briefly, the Lax-Wendroff scheme is second order and was found to produce less numerical distortion in peak discharge rates. The basic tool in this study is a general program for the kinematic cascade using this method. As programmed by Woolhiser, channel flow is turbulent and assumes the Chezy relationship. Flow over the planes begins as laminar flow with a transition to turbulent flow if a transitional Reynolds number is reached.

The coefficient α incorporates slope and roughness. The Darcy-Weisbach friction factor is f, so that:

$$f = K/R_e \tag{21}$$

for laminar flow, and:

$$f = 8g/C^2 \tag{22}$$

for turbulent flow where:

f = Darcy-Weisbach friction factor
K = roughness coefficient
R_e = Reynolds number
g = gravity constant
C = Chezy C

To match friction factors as given by eqs.21 and 22 at the transition from laminar to turbulent flow, it must be that:

$$C = (8g/f)^{\frac{1}{2}} = (8gR_c/K)^{\frac{1}{2}} \tag{23}$$

where R_c is the transitional Reynolds number. Thus, the roughness is described by the coefficient, K, and a transition number, R_c. With these relations the coefficient, α, is:

$$\alpha = 8gS/K\nu \tag{24}$$

for laminar flow, and:

$$\alpha = C\sqrt{S} \tag{25}$$

for turbulent flow, where C is given by eq.23, S is the bed slope, and ν is the kinematic viscosity.

For open-channel flow any of several handbooks (e.g., King and Brater, 1963; Barnes, 1967) can be used to estimate Chezy coefficients directly or from tabular values of Manning's n. Roughness coefficients for overland flow are presented in a table given by Woolhiser (1974) as a compendium of experimental data derived from a literature review. The same data are presented graphically by Lane (1975).

Summary of modeling procedure

The basic modeling procedure used here consists of a topographic analysis section and a hydrologic analysis section. The topographic analysis consists of: (1) determining kinematic cascade geometry; (2) calculating topographic goodness-of-fit statistics; and (3) making initial estimates of roughness coefficients. The hydrologic analysis consists of: (1) calculating infiltration and rainfall excess for given rainfall and runoff data; (2) solving the kinematic wave equations for the kinematic cascade producing simulated runoff hydrographs and optimum values for the roughness coefficients; and (3) calculating hydrograph goodness-of-fit statistics. These procedures are summarized in a block diagram as shown in Fig. 1. Input to the finite-difference program is the kinematic cascade geometry, initial roughness coefficients, estimated rainfall excess, and observed runoff data. Output from the finite-difference program consists of simulated runoff hydrographs, optimal roughness coefficients, and a hydrograph goodness-of-fit statistic.

If the mean discharge from an observed hydrograph is $\bar{q}$ then:

$$\bar{q} = \sum_{i=1}^{m} (q_i)/m \tag{26}$$

where q_i are observed hydrograph ordinates and m is the number of ordinates. The sum of squares about the mean discharge is then:

$$S_Q^2 = \sum_{i=1}^{m} (q_i - \bar{q})^2 \tag{27}$$

If the simulated hydrograph ordinates are $\hat{q}_i$ then the sum of squared errors is:

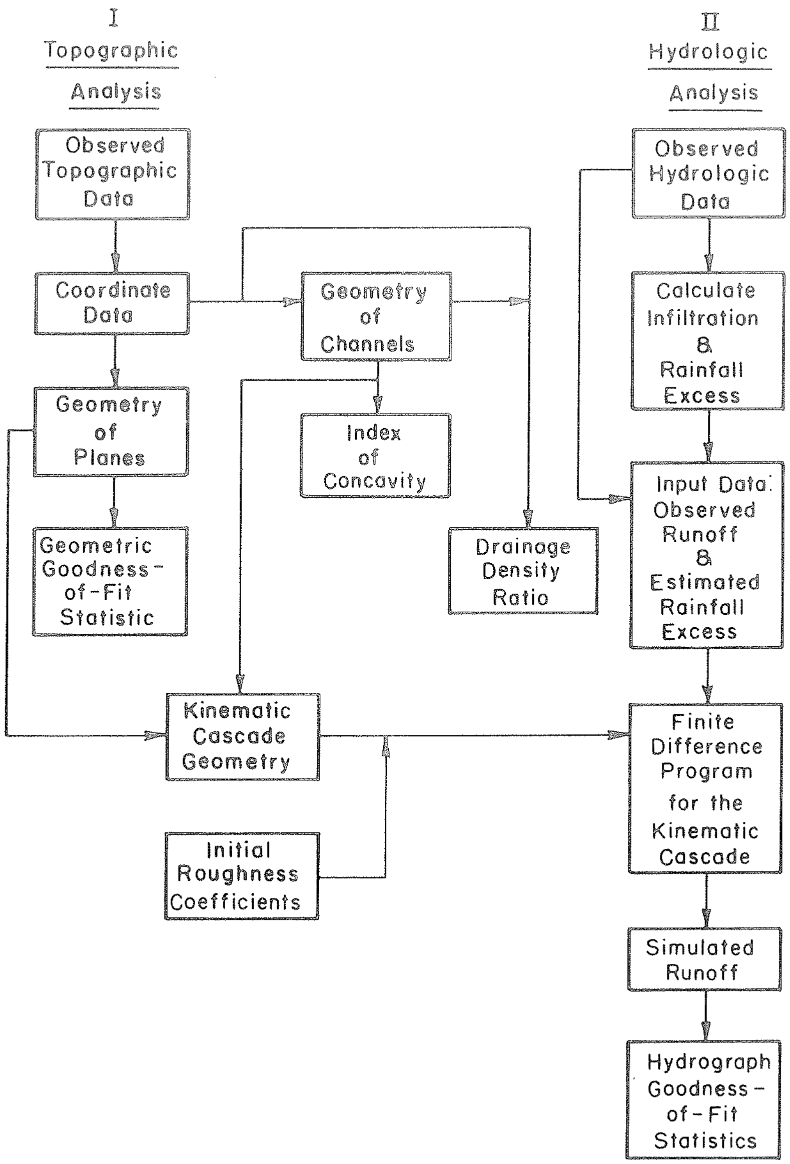

Fig.1. Block diagram summarizing the modeling procedure.

$$S_F^2 = \sum_{i=1}^{m} (q_i - \hat{q}_i)^2 \tag{28}$$

for the same number of ordinates. The hydrograph goodness-of-fit statistic is then:

$$R_Q^2 = (S_Q^2 - S_F^2)/S_Q^2 \tag{29}$$

as the degree of improvement, by fitting the optimized hydrograph, over using the mean discharge.

ANALYSIS AND RESULTS

Influence of geometric simplifications

Geometric simplification is the substitution of a simple geometry for a more complex one. A watershed characteristic is preserved if its value remains unchanged in the simplified geometry. Otherwise, the characteristic is distorted as represented in the model. Watershed area, main channel length, and main channel equivalent slope are generally preserved, while stream order, drainage density, other channel characteristics, and hydraulic roughness coefficients are usually distorted. The degree of distortion for most other characteristics falls between these extremes.

The slope shape of overland-flow surfaces affects the magnitude and time of occurrence of peak discharge of the overland-flow hydrograph. Overton (1971) considered the influence of slope shape upon overland flow. However, Overton considered steady-state conditions so that peak discharge was not a part of his analysis. He concluded that slope shape has little effect upon his lag or hydrologic response time which is related to equilibrium time. However, minimum time differences will be at equilibrium so that these results are as expected: for this reason, data from the Pawnee watersheds in Colorado, (cf. Smith and Striffler, 1969) were examined to determine the influence of slope shape upon overland flow from natural watersheds. These watersheds do not have well-defined channels. A calibrated kinematic cascade model was used to simulate runoff from concave and convex watersheds, each with a drainage area of 0.5 ha and similar in most other respects. The simulation results suggested differences in time to peak of the hydrographs of about 20% with only about 5% difference in peak discharge. Mid-watershed slope profiles produced an index of concavity of 0.76 for the concave watershed and 1.09 for the convex watershed. Under these conditions, slope-shape effects on overland flow may be significant with respect to time to peak but are probably not significant with respect to peak discharge.

Usually downstream channel slope is distorted in assuming a uniform slope when the channel slope is actually concave. Effects of such distortions include underestimated time to peak of the routed hydrograph and overestimated peak discharge. The magnitude of errors in routed peak discharge are related to the index of concavity. Finally, the magnitude of the errors is less when an equivalent (Gray's) slope is used than when slope is estimated as the total relief over the total channel length (Lane, 1975).

Drainage density is a single number representing many complex interactions of factors affecting surface runoff. For example, if overland flow is assumed to be at least partially laminar depending upon the length of flow, then drainage density is related to the relative proportion of laminar flow and turbulent flow as it represents the mean length of overland flow. Analysis of experimental data (Lane, 1975; Lane and Parker, 1975; Parker, 1975) suggested that lag time (as the first moment of an instantaneous unit hydrograph) was related to drainage density. Drainage density is map-scale dependent, but for a given map its determination is repeatable. When other factors are held constant, mean lag time decreases as drainage density increases. Gross underestimation of drainage density could result in overestimating the lag time and degree of nonlinearity and underestimating peak discharge. Suppose for the moment that lag time and peak discharge are fitted in an optimization procedure but that drainage density is underestimated. A likely result is underestimation of hydraulic roughness or a similar compensating error in another factor.

The effects of distorting slope shape in overland and open-channel flow and of distorting drainage density are significant modifications of the surface runoff hydrograph. Quantifying the hydrologic effects of these distortions resulting from simplifications assumed in mathematical modeling is difficult due to the complexity of the problem. However, goodness-of-fit statistics have been proposed to quantify the degree of distortion and its effect upon surface runoff hydrographs.

Relation between goodness-of-fit statistics

The first three steps in the modeling procedure described in Fig.1 are illustrated in Fig.2. First, a given watershed produces an observed hydrograph as shown in the left-hand part of this figure. Second, a single plane is fit to topographic data (x,y,z coordinates) producing R_1^2 as a geometric goodness-of-fit statistic. The equations of overland flow are solved for the given rainfall input producing the fitted hydrograph as the dashed line in the central portion of Fig.2. From the observed (q) and fitted ($\hat{q}$) hydrographs a goodness-of-fit statistic, R_Q^2, is computed. Third, the procedure is repeated for two planes and one channel (Wooding model) as shown on the right in Fig.2. The Wooding model also produces two other goodness-of-fit statistics; I_c, the index of concavity, and I_d, the drainage density ratio.

The finite-difference program determines optimal roughness values for the planes and channels separately. The procedure is to find optimal roughness values for K on the planes given a Chezy C in the channels. The procedure is repeated over a range of channel parameters to find the best set of roughness coefficients. Values of the objective function are shown in Fig.3. Rainfall excess is estimated using the Philip (1957) equation:

$$f(t) = A + \tfrac{1}{2}St^{-\frac{1}{2}} \tag{30}$$

where $f(t)$ is infiltration rate, t is time, and A and S are parameters. This infiltration equation obviously represents a simplified approach. However, it is a

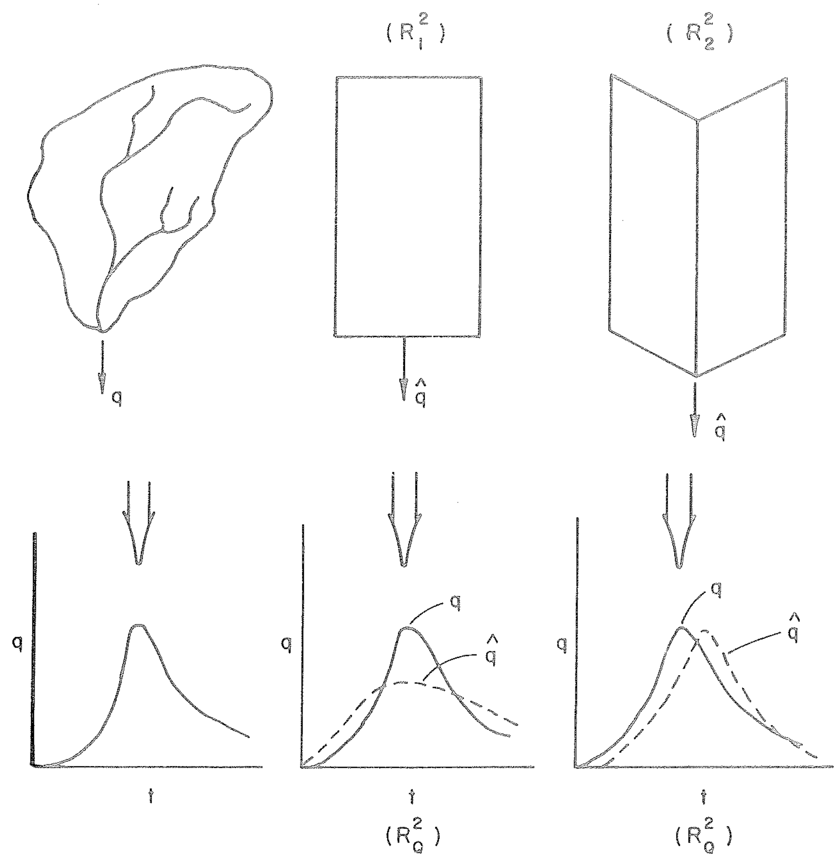

Fig.2. Schematic representation of a watershed, simplified models, and associated goodness-of-fit statistics.

simple equation and the procedure is repeatable which is all that was intended. Data used in this example are from watershed W-C at Riesel, Texas (USDA, 1963). The upper part of Fig.3 shows the objective function (eq.28) and associated optimal values of K for each of four values of C in the channel. The lower part of Fig.3 is a plot of channel C vs. plane K for this example.

Observed and fitted hydrographs for the event of 6/10/41 on watershed W-C Riesel, Texas, are shown in Fig.4. The hydrograph labeled (*0*) is the observed surface runoff resulting from the rainfall pattern shown. The curve labeled (*1*) is the best-fit hydrograph for a single plane with $R_Q^2 = 0.78$. The curve labeled (*2*) is the best-fit hydrograph for the Wooding model with $R_Q^2 = 0.95$.

Data from watershed W-C (234 ha) at Riesel, Texas, and watershed 2-H (1.38 ha) at Hastings, Nebraska, were obtained from USDA Miscellaneous Publications. Data from the 0.012 ha Drainage Evolution Research Facility

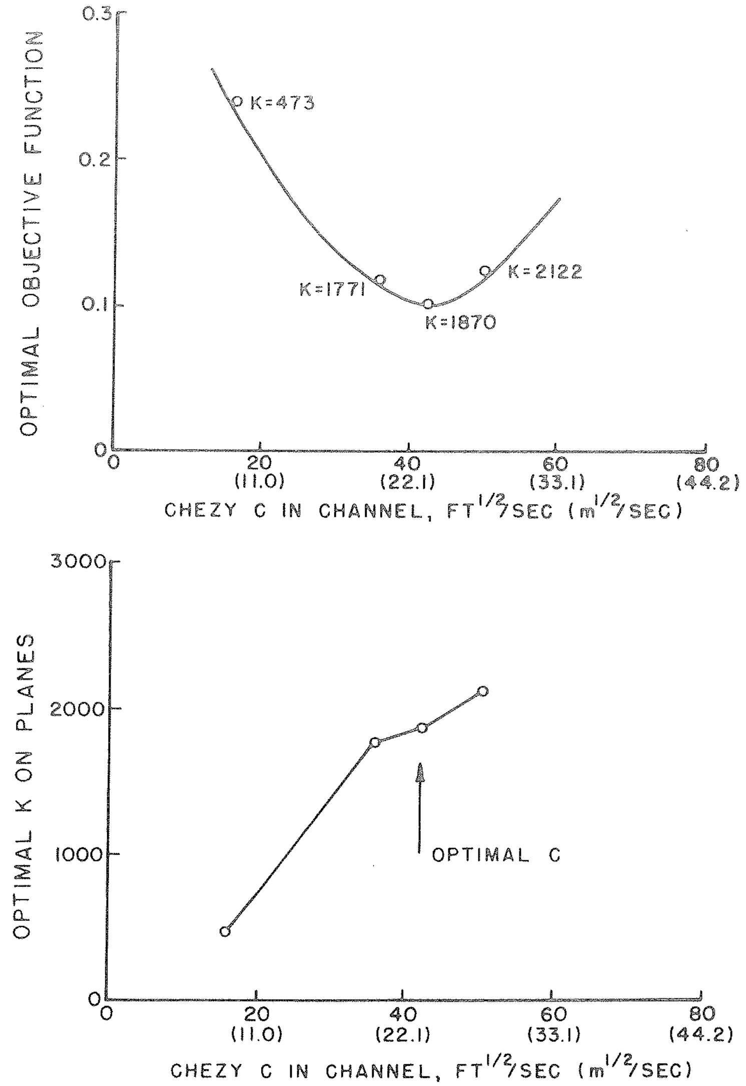

Fig.3. Illustration of procedure for selection of optimal Chezy *C* in the Wooding model, W-C, Riesel, Texas. Event of 6/10/41.

(DERF) at Colorado State University were obtained from R.S. Parker (see Parker, 1975). Data from 25 rainfall runoff events on four watersheds were analyzed as described previously, specifically as summarized in Fig.2. Relations between geometric and mean hydrograph goodness-of-fit statistics are shown in Fig.5. The left most points in Fig.5 are for a single plane and the right most points are for Wooding's model. A third geometry, as discussed later, is also shown for watershed W-C. Values of drainage density (in ft./ft.^{2}

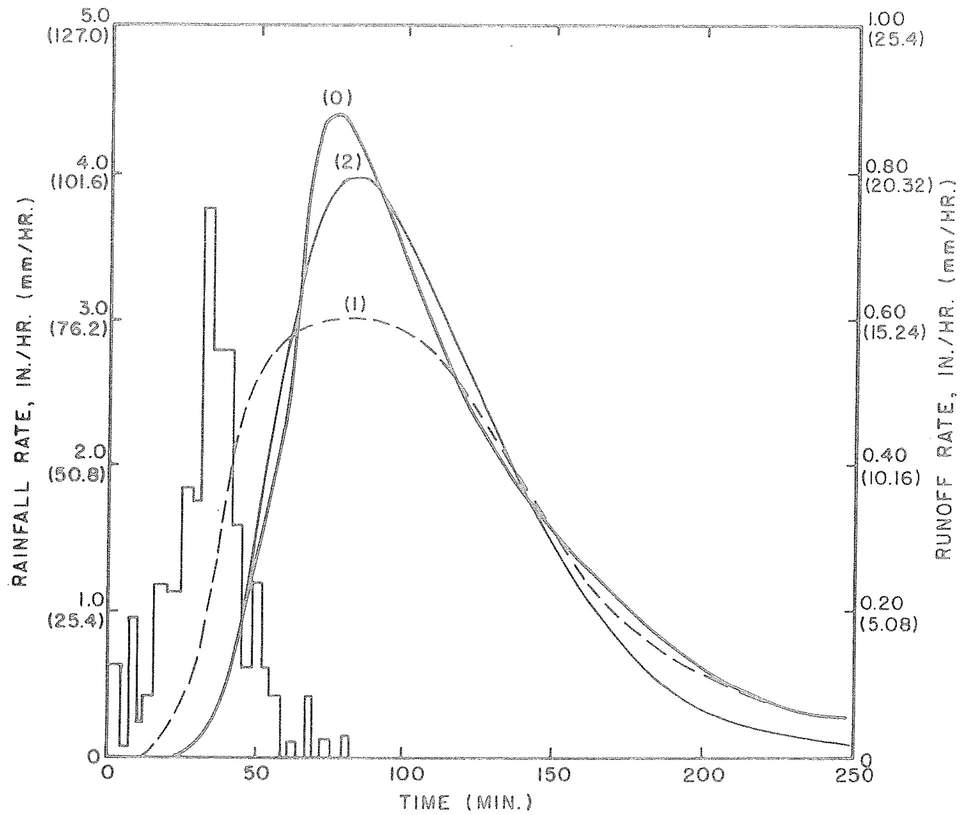

Fig.4. Observed and fitted hydrographs for watershed W-C, Riesel, Texas. Event of 6/10/41.

and m/m^2) are given below the watershed identification in Fig.5. The geometric goodness-of-fit statistic is a valuable measure of how well the watershed topography is represented in a model, but it must be interpreted with respect to drainage density.

Data from the four very different watersheds described above produced optimal roughness coefficients (K values) for a single plane and the Wooding model as illustrated in Fig.5. These optimal K values were normalized by tabular values of K_o corresponding with surface descriptions and laboratory flume studies, as described and tabulated by Woolhiser (1974). A combined goodness-of-fit statistic as the product of I_d, the drainage density ratio, and R_p^2, the geometric goodness-of-fit statistic, was then related to the normalized roughness coefficients. The statistic $I_d R_p^2$ is assumed zero for a single plane with an upper limit of 1.0 for perfect geometric correspondence. Data from the four watersheds are shown as the circled points in Fig.6.

Watershed SW-17 is a 1.21-ha watershed at Riesel, Texas (see USDA, 1963); watershed LH-6 is a 0.43-ha watershed near Tombstone, Arizona (see Renard,

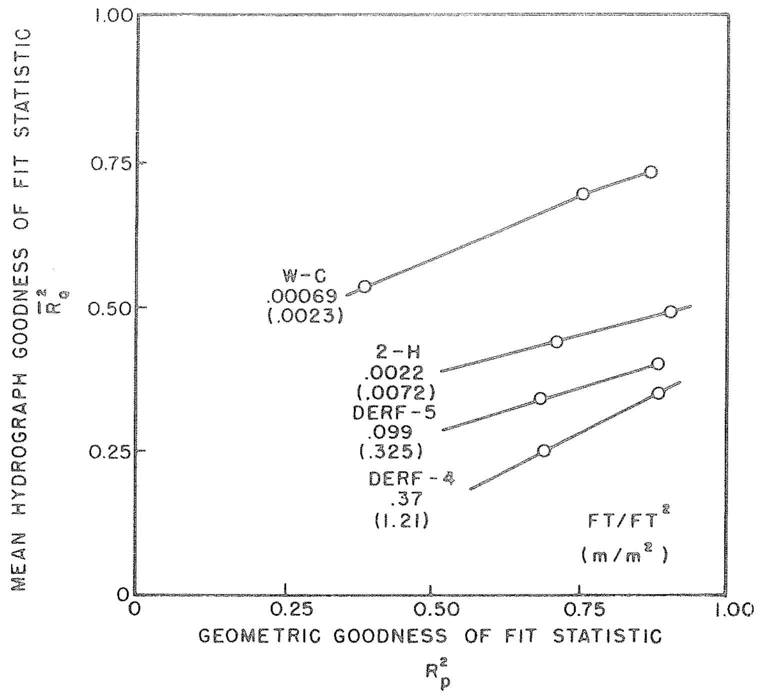

Fig.5. Relation between geometric and hydrograph goodness-of-fit statistics for watersheds with different drainage densities.

1970), and the Pawnee watersheds do not have well-defined channel systems. A more complex model for W-C consists of two channel segments in cascade and four planes. The geometry for LH-6 consists of nine planes and three channels. Data for these two watersheds are shown as the plus signs in Fig.6. Data for SW-17 and the two Pawnee watersheds are shown as the arrows in Fig.6. The two test cases (W-C and LH-6) agree with the least-squares line shown in Fig.6, and K/K_o values for SW-17 and the Pawnee watersheds define a range of about 0.25. There are no $I_d R_p^2$ values for SW-17 and the Pawnee watersheds so that their K/K_o ratios are shown at the right of Fig.6.

The major difficulty with data as presented in Fig.6 is the subjective nature of the a-priori roughness parameters. For this reason, the equation relating K/K_o and $I_d R_p^2$ represents a sample and thus may be unique. However, optimal roughness parameter estimates will likely increase as the geometric distortions in simplified models decrease.

A second cautionary note is with respect to the selection of geometric properties to be preserved in modeling a watershed. The length of the main channel, L_c, is preserved here. However, other length measures, such as the mean length of overland flow, L_o, could be chosen. Limited experience suggests that for a single plane the optimal length (with respect to the hydro-

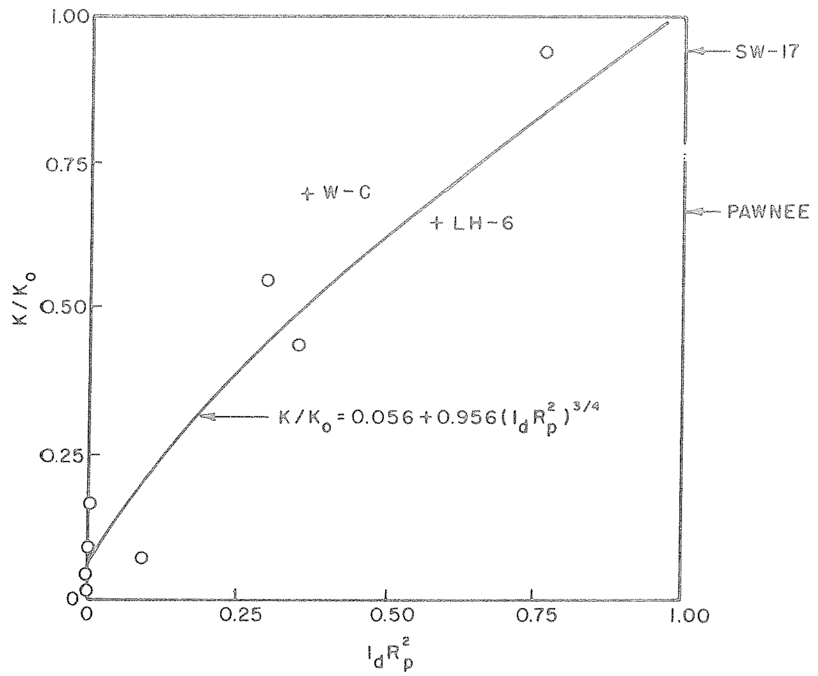

Fig.6. Relation between combined goodness-of-fit statistic and normalized roughness coefficient.

graph goodness-to-fit statistic) may be somewhere between L_o and L_c. The choice of characteristics to preserve depends upon the modeling objectives.

SUMMARY AND CONCLUSION

Summary

In formulating the equations describing the flow of water on the surface of a watershed, geometric simplifications must be made. Watershed geometry is represented by a series of planes and channels in cascade. When overland flow and open-channel flow in the cascade are described by the kinematic wave equations, the resulting mathematical model is called the kinematic cascade model. Statistics of the simplified geometry are related to statistics of the simulated runoff hydrographs and to watershed characteristics.

Conclusion

Given rainfall, runoff and topographic data for a small watershed, it is possible to define the simplest kinematic cascade geometry which when used in simulation will, on the average, preserve the selected hydrograph characteristics to a given degree of accuracy.

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