RUNOFF MODEL FOR WATERSHEDS OF NONHOMOGENEOUS HYDROLOGIC CHARACTERISTICS

by

Richard J. Heggen
Associate Professor of Civil Engineering
The University of New Mexico
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ABSTRACT

A watershed of any configuration, topography, spatial distribution of cover and soil, and channel characteristics is described as a nonhomogeneous finite-element surface grid. Time-varying precipitation is applied to the watershed and runoff is hydraulically routed over the surface in discrete time increments. Infiltration is abstracted by a variable rate model derived from SCS curve numbers. Precipitation infiltrates, stands, and/or runs off each quadrant in accordance with that quadrant's slope and hydrologic characteristics. Overland flow is routed to channels, and channel flow is then routed to the basin's point of discharge. The grid definition of the watershed surface makes the model appropriate for watersheds not adequately modeled by conventional, nondistributed hydrologic means. The model does not require that unit hydrographs or times-of-concentration be estimated.

Keywords: *small watersheds, *hydrologic models, *runoff, *watershed studies, *floodrouting, hydrology, water yield, infiltration

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INTRODUCTION

Background

Surface water discharge in much of the western United States is substantially and proximately influenced by discrete storms. Such storms precipitate significant rainfall on watersheds in relatively short periods. This rainfall may be abstracted by vegetative interception, infiltration, and surface detention. The remaining precipitation is conveyed first as overland flow and then as open channel discharge.

Water resources engineering issues stemming from discrete storms include groundwater recharge, flood protection, water conservation, and sediment transport. These issues can be adequately addressed only if the runoff behavior (the disposition of water) is understood over the short duration of the storm and its aftermath.

Runoff behavior may be difficult to anticipate if nonuniform slopes, soils, and vegetation exist within a watershed. Such varied combinations of hydrologic characteristics yield unique rainfall-runoff relationships. From the same storm, a watershed that has steep impervious slopes along one tributary but mild, sandy terrain along another may have runoff higher and earlier than a neighboring watershed which has similar characteristics in dissimilar combinations or placement.

Efficient evaluation of discrete storm runoff from such nonhomogeneous watersheds requires analytic strategy. Site-specific hydrologic diversity must be accounted for with a resolution sufficiently microscopic to distinguish dissimilar behaviors within the watershed.

Simultaneously an overall analysis that facilitates a rational hierarchy of data management must be structured.

Models

Mathematical models, computational descriptions of physical systems, are often employed in runoff studies (Overton and Meadows, 1976). Mathematical models require a presumptive theoretical understanding of the physical laws governing the modeled behavior. Components of the runoff process (infiltration, surface flow, etc.) must be explicitly detailed and linked by appropriate equations. A scheme of analysis must be devised to store and retrieve data in a logical and reproducible manner. Given a specified mathematical form (i.e., identifying the proper type of equation), mathematical constants within the model must be discovered to reproduce independently-observed behavior. Once a model can reasonably explain natural processes, a sensitivity analysis can yield significant information about the system's dependence.

Mathematical models should be transportable. If two systems are similar in structure, it should be possible to modify a model of one to explain the other. Such modification is not necessarily easy because a variety of constants may need to be altered; it is, however, generally more productive to determine new values than to reinvent the entire model. If two systems are not similar (i.e., they are based on dissimilar submechanisms that are mathematically expressed in fundamentally different forms), the model cannot be successfully transported. The solution of many hydrologic equations is complex. Although a few mathematically unsophisticated calculations (e.g., the rational method) continue in use, watershed modeling is increasingly done by digital simulation (Claborn and Moore, 1970).

There are three general classes of computerized watershed models; each is appropriate for given tasks. The first class is that of the hydrologic megamodels, most notably the Stanford Watershed Model (Crawford and Linsley, 1966, Clarke, 1968). Such models can describe the complex hydrologic interdependencies of large regions over extended periods. Such a megamodel should be employed to analyze over a long term a large river basin linked to an aquifer. Unfortunately for smaller studies, these models rely on a multitude of gross regional lumped parameters. The output is generally more adequate for identifying regional trends and sensitivity than for describing in sufficient detail the local runoff response of occasional storms.

The second class of watershed models is the hydrologic discrete storm model. The Corps of Engineers' HEC-1 (U.S. Army Corps of Engineers, 1973) and the Department of Agriculture's HYMO (Williams and Hann, 1973) are such models. Each is based on empirical statistics of watershed behavior. This modeling is appropriate for watersheds having hydrologic characteristics (e.g., storm type, ground cover, soil type, and basin shape) consistent with those for which the models were developed (Porter, 1975). Unfortunately, many watersheds have unique attributes which significantly modify runoff behavior.

A third class of watershed models is the hydraulic description; these are often restricted to catchments of prescribed shape, uniform roughness and slope. Although many such models are not well suited to field conditions, they have a potentially high value in runoff modeling of well-defined systems, e.g., converging surface flow in small areas (Sherman and Singh, 1976, Ellis and Ramsey, 1980) or cascading flow in channelized discharge (Kibler and Woolhiser, 1970). While these two mechanisms may not be independently good descriptions of natural runoff, of a larger explanation they may be valid components. Hydraulic description reduces the modeling complications for a nonhomogeneous watershed. Basin characteristics need not be lumped or generalized; but rather at a small scale, runoff can be evaluated by physical laws.

The Environmental Protection Agency's hydraulic model is SWMM (U.S. EPA, 1971). This model, however, was developed for urban conditions. The U.S. Department of Agriculture's HYMO, fundamentally a hydrologic model, has been hydraulically adapted for urban use (Easterling, 1979), but application remains most appropriate for a basin where only lumped-parameters can be assumed.

There remains a need for a general-purpose hydraulic model suited for nonhomogeneous conditions. Such a model should draw from the theoretical basis employed in the hydraulic formulations, while retaining the flexibility necessary for a variety of applications. Since a great deal of empirical survey and testing data exists for some hydrologic parameters (e.g., soil type and cover complex), this information can be employed to adjust constants within the hydraulic formulation.

Study Design

This study develops a discrete storm runoff hydraulic model appropriate to watersheds of nonhomogeneous hydrologic characteristics. The study approach involves three steps, briefly introduced below.

Step 1. A watershed's surface is described by an arbitrarily-oriented planar grid of quadrants. Each quadrant is described by elevation, soil and cover characteristics, and fluvial geometric parameters. Both site survey and published data may be required. Soil survey data, for example, is needed for subsequent transformation into variable-rate infiltration to model time-dependent abstractions.

A general case discussion of this step follows in the WATERSHED DESCRIPTION section of this report.

Step 2. By mass balance, runoff is dynamically routed over the grid surface. Surface flow concentrates into channels; infiltration depletes both surface and channel storage, and discharge is transported to downstream quadrants. Finite differences are used to compute the intergrid discharges. The various hydrologic processes are explicitly defined. The dynamic response requires computational updating at each time step. The model is structured to facilitate computational modification to improve its performance for particular cases.

This step is sequentially explored in the sections RUNOFF SIMULATION through PARTITIONING.

Step 3. The final step is illustration by case study. Two case studies are described; one is in an urbanizing mountainous watershed, the other an undeveloped mesa area. The first case study employs the model in its basic form. Emphasis is placed on data setup and output interpretation. In the second study, the model is modified to reflect results from infiltration field work and synoptic stream gaging. Emphasis here is placed on verification against independent measures.

These cases are described in the DEMONSTRATION ANALYSIS and VERIFICATION ANALYSIS sections of this report.

WATERSHED DESCRIPTION

Quadrants

A surface nonconvoluted in direction h is a surface in which a normal vector at every point on the surface has a nonnegative h-component. In a cartographic sense, a nonconvoluted land surface is one having no overhanging cliffs; consequently, from overhead, everything can be seen. Contour mapping of convoluted landform requires the intersection of contour lines. Contour mapping of nonconvoluted surface does not. This model is only appropriate for nonconvoluted surfaces.

The planar projection of a nonconvoluted land surface may be overlaid by a grid of constant spacing. Were this done in the field, an area would be marked by surveyed markers of regular horizontal spacing in orthogonal directions. Done at a table, a map of the area would be gridded by evenly spaced horizontal and vertical lines. In either case the surface can then be described as a set of contiguous quadrants. Quadrants spanning the surface boundary will overlay a portion of the surface and a portion of adjacent (nonsurface) area. In such cases, quadrants more than half filled with surface can be considered to be entirely filled. Quadrants less than half filled can be considered to be entirely empty (thus, they are effectively no longer part of the surface). Quadrants exactly half filled can be taken as filled or empty on a random basis.

As a quadrant's size decreases, the resulting configuration of filled surface quadrants more accurately resembles the shape of the original surface. At the same time, the computational effort to simulate surface-dependent behavior increases in a cubic manner. Thus there is a tradeoff between precise boundary matching and resulting modeling effort.

The runoff model developed here allows for a watershed to be defined within a 30 x 30 quadrant grid although this limit could be expanded. The model recognizes watershed boundaries by empty quadrants adjacent to full quadrants; at least one column on the left and one on the right and one row at the top and one at the bottom must be empty. Thus the actual watershed must fit within a 28 x 28 grid. This limit imposes a lower constraint on quadrant size, no more than 1/28 of the larger of either the basin's length or its width.

If a grid size is selected where less than 28 quadrants are utilized in either the horizontal or vertical direction, the watershed can be arbitrarily shifted within the 28 x 28 grid overlay. Quadrant rows can go from 2 to 12, 10 to 20, or 18 to 28 if the basin is 11 units wide.

There is no requirement that quadrant row-column coordinates correspond to compass directions. To be more smoothly defined by quadrants, a diamond-shaped watershed might be rotated in respect to the grid direction.

One empty quadrant adjacent to the watershed must be identified as the basin's outflow "gaging-station". This quadrant, immediately downstream of the quadrant through which the basin drains, is used to monitor the total basin discharge.

Quadrant Parameters

Topographic and hydrologic characteristics must be specified for each gradient of the watershed. In cases where a particular parameter (e.g., soil type) is uniform over the entire watershed, the program can be modified to automatically assign the given value to each quadrant. Antecedent moisture condition, average length of surface flow until runoff enters a well-defined watercourse, channel sinuosity factor, and channel hydraulic roughness are so assigned in the model. In some cases, these variables may not be uniform and must be assigned on a quadrant-by-quadrant basis.

Every watershed quadrant is identified by row and column in the quadrant grid. Each quadrant is assigned an elevation taken by map or survey at the quadrant center. Subsequent analysis (see PARTITIONING QUADRANT OUTFLOW) uses these elevations to estimate the direction of runoff through the watershed. Elevation data is indirectly used to compute surface and channel velocities. Although the model could be modified to include filling impoundments within a watershed, it is assumed that all nonabstracted rainfall continuously flows along a downhill path until it leaves the basin. Thus there must be a downhill pathway from every point in the watershed. This condition is achieved in the model by each quadrant having at least one adjacent quadrant of lower elevation ("adjacent" being to the left, right, above, and below). A sump quadrant (one having no lower adjacent neighbors), cannot be present. If, in fact, it appears that terrain is perfectly flat over a group of quadrants, the elevations of an appropriate few must be slightly deviated to avoid computational difficulties. This same modification is often done in open channel hydraulic computations where a horizontal bed is encountered.

The remaining quadrant descriptive variables are specifically related to the hydrologic processes included in the model. Three parameters are used in this illustrative report, though others might be required to suit alternative computations. These three are hydrologic soil group, vegetative cover complex, and vegetative cover density; all of which are used in infiltration estimation. The INFILTRATION section of this report discusses the values and uses of these variables.

RUNOFF SIMULATION

General

The watershed runoff model has discrete form; time progresses in constant finite steps and hydrologic processes occur as discrete sequential events. Because the time steps have a short duration in relation to the overall runoff process, the model's output approximates a continuous description.

The model simulates runoff by describing quadrant states, intra-quadrant processes, and interquadrant interfacing. Since interfacing is updated at the start of each time step, it makes no difference in what order the quadrants are evaluated.

State Variables

Three nonnegative state variables describe each quadrant. Surface storage is the volume or depth of water standing on the nonchannalized portion of the quadrant. This storage must eventually either be abstracted or enter a channel. Subsurface storage is the volume or depth of water that has infiltrated from the surface. Channel storage is the volume of water in open channel flow, draining to adjacent quadrants. Figure 1 shows these state variables as boxes.

At the start of any time step, each quadrant has some nonnegative quantity of water on the ground as surface storage, beneath the ground surface as subsurface storage, and in defined water courses as channel

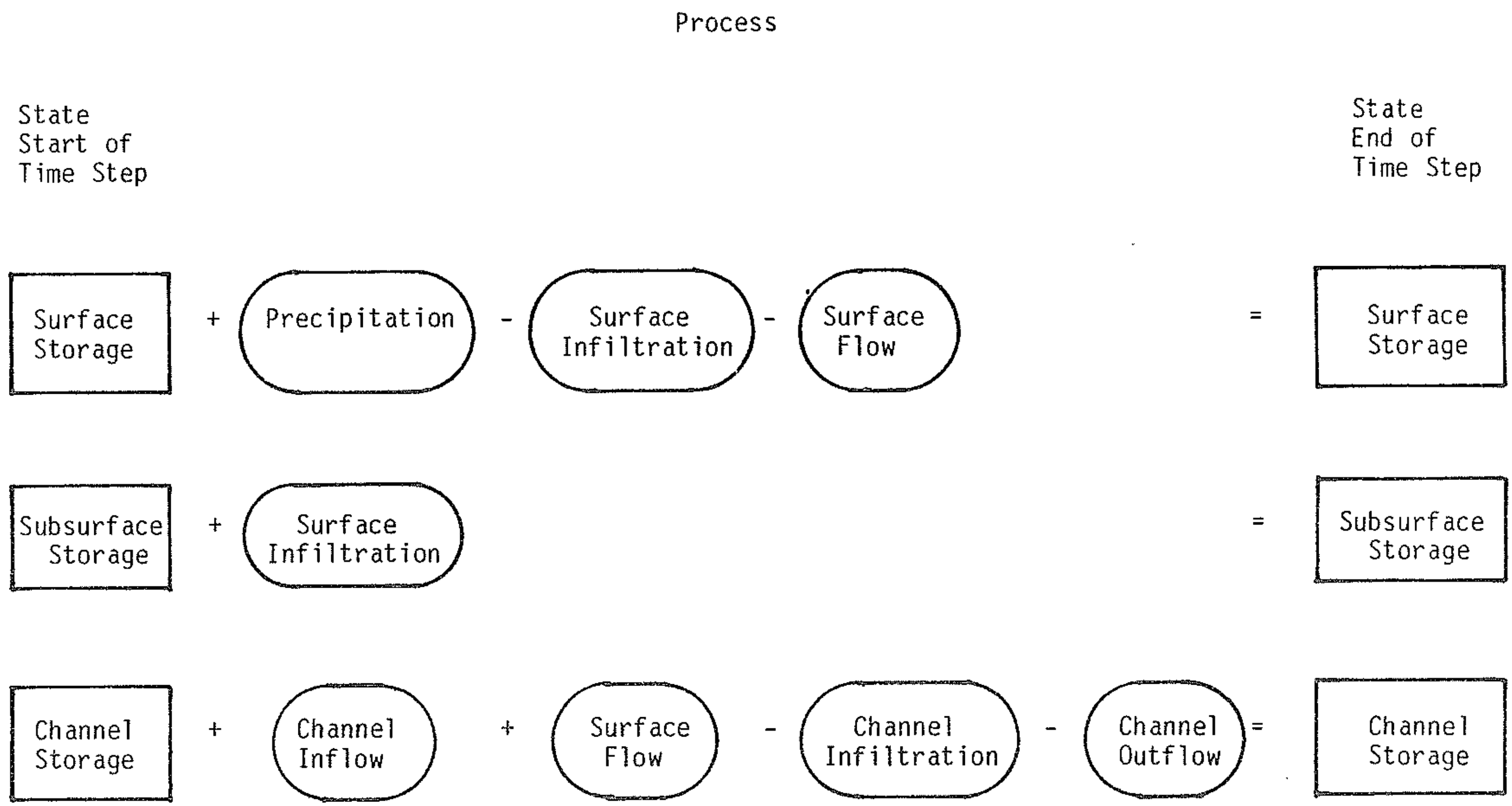

Figure 1. Process sequence.

storage. For a rainfall event occurring after a long dry spell, at initial conditions all of these storages may be zero.

Process Sequence

In any quadrant over one time step, six discrete processes may occur. These processes are 1) precipitation input, 2) infiltration from the surface, 3) surface flow, 4) channel inflow, 5) infiltration from the channel, and 6) channel outflow. These processes are identified as oblong entries on Figure 1.

Read left to right, line by line, Figure 1 indicates the sequence of process simulation. The mathematical formulations for state and process calculations are detailed later in this report, but the overall model can be briefly outlined and brought together at this point.

A depth of rain falls during the time step. This depth is assumed to occur evenly over the quadrant surface and is added to the existing surface storage. It is assumed that rainfall directly into channels is negligible. Program modification for rainfall directly into the channel would be possible.

Before any water runs off the surface, abstractions must be satisfied. It is assumed that the principal abstraction is infiltration. Additional abstractions might be lumped into infiltration, removed from the rainfall, or be added to the model as additional processes. Infiltration depends upon soil characteristics, the available water in surface storage, and the remaining capacity for subsurface storage.

After abstractions, a portion of the surface storage runs to a channel as surface flow, leaving a residual surface storage for the next time step.

Infiltration is added to previous subsurface storage to be carried forward to the next time step. Since the model is for single event surface runoff, the ultimate fate of the subsurface storage is not determined.

At the start of a time step, channel inflow from upstream adjacent quadrants is summed and added to any existing channel storage. To this is added surface flow from the quadrant over the time step. A portion of this channel storage is infiltrated into the bed. Again, the subsequent disposition of this abstraction is not estimated.

Some of the remaining channel storage flows downstream. Partitioning involves the proportioning of channel outflow between more than one adjacent quadrant of lower elevation. Channel outflow is partitioned and as channel inflow, it is brought into the downstream adjacent quadrants in the next time step.

The entire process is iterative. Each quadrant is modeled for a single time step. States are updated and interquadrant flows computed. The time step is advanced, states carried forward, and flows passed along.

Limits

Model limits fall into three categories. The first limit, that of the suitability of process equations, is obvious, and if need be, must be rectified by program modification. The computation of event processes (e.g., how much rainfall is infiltrated) must represent a balance between sound theory, practical data availability, and computability. The equations presented in this report represent one such subjective balance. Other investigators might choose alternative expressions. Thus, the model (as are all models) is limited to applications where the computational basis is appropriate to the physical behavior being described.

The second limit deals with parameter values. Few hydrologic equations are expected to be valid over a wide range of mathematically-calculatable solutions. Care must be taken that values employed in the simulation be within a range hydrologically appropriate for the equations.

The third limit, time step duration, is more subtle than the first two; however, if it is violated, it can devastate the results of a simulation. If the time step is too great, two types of errors may occur. The first error is due to sequential summation. For processes where quantities are added and subtracted, intermediate totals must be reasonable if other processes use these totals in subsequent calculation. For example, initial channel storage, channel inflow from upstream, and surface flow into the channel for a time step are combined to form an intermediate total that is then used to compute channel outflow. If the time step is long, surface and channel inflow may be great, and the subsequent intermediate total will indicate storage subtantially greater than that in the channel. Because open channel discharge generally varies in some exponential relationship with stage, the outflow error will vary exponentially with the storage error. The degree of such bias can be reduced to a negligible level if the intermediate sequential summations resemble the actual physical state. Time steps should be short enough that process changes are small compared with states.

Secondly, long time steps lead to quadrant interface errors. Because channel flows are only passed at the start of a time step, the most rapid runoff over the longest flow path in a watershed will take n time steps where n is the number of quadrants traversed. Since n is fixed by geometry, the minimum duration is thus proportional to the time step size. Time step duration dt must be such that ndt is less than the time of concentration.

When actual travel time through a quadrant is less than the time step, the model incorrectly postpones the outflow from a quadrant until the next iteration. A similar delay may result for surface flow within the quadrant; if the time step is longer than the overland travel time, surface flow is unrealistically restrained from entering the channel.

A general rule is suggested for achieving an adequately short time step. Estimate the minimum time required for each type of event (e.g., travel time overland, travel time through quadrant, and time for infiltration to occur). The minimum of these minimums, divided by four is a reasonable first-try time step.

Sensitivity should be used to refine the time step. When time steps are too large, the simulation results will vary. As the step size is decreased, results will converge.

PRECIPITATION

General

Although many hyetographs are roughly triangular, peaking at approximately the third point, the hydrologic response of a watershed from any irregularly-distributed storm may be significant (Burnette, 1980, Osborn, et al., 1980, Fogel, 1969, Hjelmfelt, 1981). The watershed model allows specification of any rainfall distribution including one embedding dry periods within a storm (thus making the model in effect appropriate for multiple events).

Time-intensity data points are input in the same manner as they would be plotted on a conventional bar-chart hyetograph. A given intensity is assumed to be of constant rate from a given time until the subsequent entry. If the last entry has a nonzero intensity value, that intensity will be maintained until the end of the simulation. It is not necessary that the rainfall time values correspond with the simulation time steps, although during that step, the effect of an intensity change within a simulation step would be missed by the model.

It is not necessary that the storm start at simulation initiation. Starting an analysis with one inch of surface water and zero infiltration rate and imposing no rainfall provides an instantaneous unit hydrograph. A similar analysis could be made by applying a 1/dt intensity for one simulation time step, dt.

Areal Modification

The basic watershed model applies precipitation with a uniform areal distribution. Minor modifications of the model, however, can generate spatially-distributed rainfall. Nonuniform areal distribution is most simply achieved by incorporating a short algorithm to proportionally increase or decrease rainfall in specified subareas of the watershed.

Consider a total watershed of area A_T to receive rainfall of mean depth $\overline{P}$ in a given period. The total watershed can be divided into n subareas, $A_1, A_2, \ldots, A_n$, respectively receiving depths $P_1, P_2, \ldots, P_n$. By definition

$$\sum_{i=1}^{n} A_i = A_T ,$$

and

$$\overline{P} = \frac{\sum_{i=1}^{n} P_i A_i}{A_T} .$$

Introducing a proportionality factor $r_i = P_i/\overline{P}$,

$$\overline{P} = \frac{\sum_{i=1}^{n} r_i \overline{P} A_i}{A_T} ,$$

or

$$A_T = \sum_{i=1}^{n} r_i A_i \ .$$

Endless sets of r exist that satisfy this equation. Often, r's can be approximately assumed from topographic factors and historical records. A mountain exposure may receive 1.2 times the areal mean rainfall while a valley may get 0.5 (Osborn, et al., 1980). Distribution may be random, one quarter of a watershed receiving, say, 1.5 times that of the remainder. If in the judgment of the investigator, spatial distribution is potentially significant, that judgement must be employed to assign proportionalities.

Assignment of r is facilitated if the subareas are of equal size. In this case, it is only required that the mean of r's be one. Program modification is simplest if subareas are easily defined by quadrant rows and/or columns. If, for example, a watershed is areally bisected between quadrant rows 19 and 20 and if it is assumed that quadrants below this division receive 0.9 $\overline{P}$ while those above receive 1.1 $\overline{P}$, quadrant rainfall should be corrected,

$$P = 1.1 \ \overline{P} \ , \quad \text{row} \geq 20 \ ,$$

$$P = 0.9 \ \overline{P} \ , \quad \text{row} < 20 \ .$$

This modification does not alter the temporal distribution of the storm. Precipitation peaks at the same time over the entire watershed. With sufficient model expansion, it is possible to simulate different (not just depth-proportional) storm patterns over different areas of a basin. Individual storm hyetographs would need to be input for respective subareas. Alternatively, a single mean storm could be used with time-varying r's. In general, however, this degree of sophistication is outside the intended scope of the model.

INFILTRATION

General

Surface infiltration of precipitation and runoff is typically the most significant hydrologic abstraction to occur. It is not uncommon in arid New Mexico for more than half of the rainfall from a semiannual storm to be immediately lost to infiltration (U.S. SCS, 1973). The fate of infiltrated water may be of major importance to the regional hydrologic budget. If the infiltrated water percolates below the soil's root zone, ground water is replenished. If the infiltrated water is retained within the root zone, vegetation prospers. If the infiltrated water remains near to the aerated soil surface, the moisture is likely to be lost to evaporation (Hachun and Alfaro, 1980).

For single-event rainfall-runoff modeling, the disposition of infiltrated water is of minor concern. Once infiltrated, water will not significantly contribute to the storm's hydrograph. If infiltrated water later exfiltrates, the effect is noted in the base flow that is superimposed on a following storm hydrograph.

There are two fundamental methods for modeling infiltration. The first can be classified as "front-end abstraction". Some water depth F is taken as a measure of a soil's water retention capacity. If a storm does not exceed F, all the precipitation is considered to immediately infiltrate and no flow runs off.

Front-end abstractions are not based upon any rate measure. Using an example F = 0.1 in., no runoff would occur from a storm that dropped either 0.1 in. in a minute or 0.1 in. in a day. For the same watershed, 0.2 in. of runoff would result from both a 0.3 in. storm of one minute duration and a 0.3 in. storm of one day duration by this method. Such an approach based on extensive rainfall-runoff records can occasionally provide a quick runoff estimate, but in general it is arbitrary and hydrologically unjustified.

The alternative to front-end infiltration modeling is a rate-based method. In its simplest form (the ϕ index), some constant rate f is abstracted from rainfall intensity. If a watershed has been extensively monitored, a constant-rate f can be back calculated.

Variable rate models are more realistic, but additionally data-intensive (U.S. SCS, 1972). Typically, the infiltration rate is exponentially decayed,

$$f_t = f_\infty + (f_0 - f_\infty)\, e^{-kt} ,$$

where f_t is the infiltration rate at time t; f_0 is the infiltration rate at inception of the infiltration process; f_∞ is the steady-state f asympotically approached as infiltration continues; and, k is a decay coefficient. The steady-state f_∞ may be nonzero for a uniformly well drained soil, but it is close to zero for soils that seal or swell, have strata of low permeability, or are of low porosity. This exponential rate model is used in this study.

Mathematical Formulation

Integrating the rate equation over time to obtain F_t, total infiltration (a depth) at time t,

$$F_t = \int_0^t f_t \, dt \ ,$$

$$= \int_0^t [(f_o - f_\infty) \, e^{-kt} + f_\infty] \, dt \ .$$

Often, f_∞ is small compared to f_o and can be approximated by zero. Thus,

$$F_t = \int_0^t f_o \, e^{-kt} \, dt \ ,$$

$$= \frac{f_o}{k} (1 - e^{-kt}) \ .$$

When t is infinite, F_∞ is f_o/k, and k equals f_o/F_∞.

The F_∞ term represents an estimate of a soil's total water holding capacity. As will be shown later, F_∞ can be estimated from soil survey data and can be considered to be an independent variable for the infiltration model. Substituting for k,

$$f_t = f_o \, e^{-\frac{f_o}{F_\infty} t} \ ,$$

and

$$F_t = F_\infty \left(1 - e^{-\frac{f_o}{F_\infty} t}\right) \ .$$

Considering the time step Δt following t, the increase in F over that interval is

$$\Delta F = F_{t+\Delta t} - F_t$$

$$= F_\infty \left(1 - e^{-\frac{f_o}{F_\infty}(t+\Delta t)}\right) - F_\infty \left(1 - e^{-\frac{f_o}{F_\infty} t}\right)$$

$$= F_\infty \, e^{-\frac{f_o}{F_\infty} t} \left(1 - e^{-\frac{f_o}{F_\infty} \Delta t}\right).$$

The time term t poses no problem if infiltration is assumed to continue over the storm and aftermath period at its exponential rate. If, on the other hand, rainfall ceases or falls below the exponentially estimated infiltration rate for periods within the storm, the infiltration process will slow for those durations. When surface water is again replenished, the process will return to its modeled rate. Time t, however, is no longer measured on a real-time clock, but rather only during periods where water capable of being infiltrated is present (Smith and Chery, 1973). The clock issue involves more than starting and stopping a timepiece. In periods where precipitation is less than the exponential rate, y, this t for the model must be measured more slowly than real time. Clearly it seems prudent to eliminate t from the expression. Rearranging the equation,

$$F_\infty e^{-\frac{f_o}{F_\infty} t} = F_\infty - F_t .$$

The right-hand term can be denoted F_R, the remaining infiltration capacity. Solving for t,

$$t = \frac{F_\infty}{f_o} \ln \left(\frac{F_\infty}{F_R}\right) .$$

The non-real-time is now expressed as a function of total and remaining capacity and the initial rate. Substituting,

$$\Delta F = F_\infty e^{-\frac{f_o}{F_\infty}\left(\frac{F_\infty}{f_o} \ln \frac{F_\infty}{F_R}\right)} \left(1 - e^{-\frac{f_o}{F_\infty} \Delta t}\right)$$

$$= F_R \left(1 - e^{-\frac{f_o}{F_\infty} \Delta t}\right) .$$

The last parenthetical term is the decimal portion of F_R that may infiltrate in a time step. Thus the infiltration over a time step is limited by the proportional infiltration capacity. Note that all the parenthetic terms are constants. This implies that ΔF remains a constant proportion of F_R if time steps remain the same, a restatement of the exponential decay basis for the model.

It is not necessary that ΔF be infiltrated. If supply is less than ΔF, the smaller amount will infiltrate. In either case, F_R will be decreased appropriately for the subsequent time step. Denoting actual infiltration during a time step as F_A,

$$F_A = \min \begin{cases} \text{surface water depth} \\ \Delta F \end{cases} .$$

Parameter Estimation

The infiltration model depends on two soil-specific parameters, F_∞ and f_0. Each can be estimated by field testing. In some cases, these parameters can be inferred from soil-survey reports developed by the Soil Conservation Service (SCS) (U.S. SCS, 1972, Aron and Miller, 1977). Field testing is suggested to confirm or modify soil survey literature but is generally not a necessary evaluation on a quadrant by quadrant basis over the modeled watershed (Hawkins, 1975, Hjelmfelt, 1980).

The F_∞ total infiltration capacity term is the same as the total potential abstraction term S in the empirical SCS rainfall-runoff relation,

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} .$$

Here, Q is runoff volume, P is precipitation volume and S is the sum of potential maximum infiltration retention (S') and initial abstraction (I_a), which incorporates detention storage, interception, etc. In SCS notation

$$S = \frac{1000}{CN} - 10 ,$$

where CN denotes a curve number. CN thus becomes a transformed estimate of F_∞.

$$F_\infty = \frac{1000}{CN} - 10 .$$

The CN depends on a variety of hydrologic factors: soil type, antecedent moisture condition (AMC), land use, cover treatment, and general watershed condition. SCS literature suggests CN's for many common land surfaces.

For the watershed model, CN can be assigned on a quadrant-by-quadrant basis if each quadrant is identified by soil type, vegetative cover complex, and vegetative cover density, and if the watershed as a whole has a specified AMC.

Soil types are hydrologically classified by the SCS as being A, B, C, or D. Deep, absorptive sands and silts typify type A and swelling, plastic clays typify type D. Soil types can be taken from 1:24000 SCS soil survey maps.

Vegetative cover complex determination generally involves field appraisal. For New Mexico's Middle Rio Grande Valley mesa terrain, five complexes are used by the SCS: desert brush (DB), herbaseous (H), mountain brush (MB), juniper-grass (JG), and ponderosa pine (PP). Each complex is described by general appearance, typical plants, and comparative location (U.S. SCS, 1973).

Cover density is estimated as the areal percent of ground shaded by plant foliage. The estimate can be made by measuring along straight lines of random location and direction, the proportional length in which plant cover is encountered. More simply, the SCS suggests a technique employing randomly located small sample squares (U.S. SCS, 1973). Generally, after a few such methodologically proper measurements, an observer can visually estimate cover density with reasonable accuracy.

For the Middle Rio Grande region, the SCS has developed a graphical estimate of CN as a function of soil type, cover complex, and cover density. Although the estimate is not a strictly linear model and does not cover all independent-variable combinations, a linear expression of the SCS curves can be approximated over the range of values likely to be encountered in the field. These approximations are

$$CN = CN_1 - P \cdot CN_2 ,$$

where P is cover density expressed as a decimal and CN_1 and CN_2 are parameters for the soil type and cover complex. These values are shown in Table 1.

Antecedent moisture may be classified as one of three conditions: Condition 1--dry soil, Condition 2--soil of average moisture content for the storm season, and Condition 3--nearly saturated soil. Curve numbers are generally computed assuming AMC is 2 and corrected for AMC other than 2. The SCS publishes in tabular form suggested CN correction for AMC is 1 and 3 (U.S. SCS, 1972). In general form

Table 1

CN_1/CN_2 Values by Soil Type and Cover Complex

Soil Type	Cover Complex				
	DB	H	MB	JG	PP
A	80/16	77/36	76/58	77/66	65/38
B	84/8	84/26	83/46	84/52	73/32
C	90/8	90/18	90/36	90/34	83/26
D	92/3	93/10	96/28	93/10	89/16

$$CN_{corrected} = F_c \cdot CN_{uncorrected} ,$$

where F_c is a correction factor depending on $CN_{uncorrected}$. F_c is computed,

$$F_c = A + B \cdot CN_{uncorrected} ,$$

where A and B are empirical constants given in Table 2. If $CN_{uncorrected}$ is 75 and AMC is 1, F_c is 0.750. If AMC is 3, F_c is 1.208. The corrected CN's would be 56 and 91, respectively.

The F_∞ term, an estimate of a soil's water-holding capacity, is not a rate, but rather it is a depth. The time dependent aspect of infiltration on the infiltration rate depends primarily upon soil hydrologic type. Because infiltration rates are highly variable, SCS literature only qualitatively distinguishes types A, B, C, and D as having "high", "moderate", "slow", and "very slow" infiltration rates when thoroughly wetted (U.S. SCS, 1977). Inch/hr f values generally associated with these designations are given in Table 3, but these values represent only some minimum rate at an unspecified long duration. Initial rates, f_o, are almost never specified for the four soil types in general case literature.

For the watershed model, it is recommended that f_o rates be field-tested. A rainfall simulator provides the best data because surface compaction by raindrops can affect f_o. Second best would be a split-ring infiltrometer. Marginally satisfactory would be a shallow

Table 2

Curve Number Correction Constants

AMC	CN Uncorrected	Constants A	Constants B
1	>85	-0.333	0.01333
	<85	0.350	0.00533
3	>40	1.833	-0.00833
	<40	2.369	-0.0217

Table 3

Infiltration Rates

Soil Group	Initial Infiltration Rate (in/hr)
A	2.00-3.00
B	1.20-2.00
C	0.70-1.20
D	0.30-0.70

bore-hole test. Again it is generally prudent to do several evaluations "by-the-book" to help quantify quicker visual surveys. Since root systems tend to loosen and the soil and humus tend to be porous, it is reasonable that soils with good vegetative cover should have a higher f_0 than would bare soils. Assuming a linear dependence of f_0 on cover density CD, f_0 can be estimated

$$f_o = f_{min} + (f_{max} - f_{min})\ CD ,$$

where f_{min} and f_{max} represent the range of f_0 for a given soil type and CD is expressed as a decimal.

A field check may be made on f_0 by timing the duration for one-half of F_∞ to infiltrate. It can be shown that

$$f_o = \frac{F_\infty}{t_{1/2}} \ln 2 ,$$

where $t_{1/2}$ is the duration required for a depth $F_\infty/2$ to infiltrate. For example, if CN = 75, F_∞ = 3.33 in. and 1.67 in. of water infiltrates in the first hour, f_0 would be 2.31 in./hr.

Channel Beds

Seepage into channel beds can be significant when beds are sandy and dry at the start of runoff. Consider the length of channalized flow in a quadrant to be L. In a subsequent section, CHANNEL FLOW, average L is shown to be 0.7 DT where D is quadrant width and T is tortuosity. Total channel storage in a quadrant is

$$C = LA$$
$$= 0.7\ DTA\ ,$$

where A is cross-sectional area of the channel. Thus,

$$A = \frac{C}{0.7\ DT}\ .$$

Typical seepage loss from ephemeral channel beds in New Mexico is estimated

$$Q = 3\sqrt{A}\ ,$$

where Q is in cfs/mile and A is cross-sectional area in ft^2. Substituting,

$$Q = 3\sqrt{\frac{C}{0.7\ DT}}\ .$$

Q can be converted from cfs/mile to ft^3/quadrant/time step by multiplying by the miles of channel per quadrant, and the time step Δt in seconds,

$$Q = \frac{\Delta t}{35}\sqrt{CDT}\ .$$

The dimensional denominator 35 reflects assumed constants. Although this value is suggested, field study may be called for to improve seepage estimation.

In the model, channel seepage is emulated without upper limit. However, minor program change can stop this abstraction at a predefined total or time.

SURFACE FLOW

General

Surface flow is the nonchannalized transport of rainwater from the point of surface impact to a delineated watercourse. Where the earth surface is smooth, surface flow may take the form of a thin sheet of fluid. Where the surface is broken by grass, small rocks, or trees, surface flow rivulets separate and merge as obstructions are encountered.

Two fundamental hydraulic models are used to describe surface flow: laminar flow and turbulent flow. Laminar flow theory assumes negligible momentum interchange between fluid particles. Flow is controlled by the viscous nature of the fluid, not the roughness of the solid surface. Velocity in laminar flow is calculated as

$$V = \frac{gSH^2}{3\nu} ,$$

where g is the gravitational constant, S is slope, H is depth, and ν is kinematic viscosity.

Turbulent flow assumes transverse fluid intermixing brought about by roughness elements on the solid boundary. Velocity is calculated by Manning's equation for wide channels,

$$V = \frac{1.49}{n} H^{2/3} S^{1/2} ,$$

where n is a Manning's roughness coefficient, or by the Chezy equation,

$$V = C\ H^{1/2}\ S^{1/2}\ ,$$

where C is a Chezy coefficient.

The safest description of surface flow would be that of a "mixed" regime. Where flow depths are small, flow will behave in a laminar manner; but where depths and velocities increase, turbulent behavior may predominate. Unfortunately, mixed regime flow models are generally highly idealized, relying on a well-defined system in which to apply boundary layer theory. Practical watershed modeling does not generally justify such microscopic precision.

Either a laminar or turbulent surface flow submodel might reasonably be employed in the watershed model. Reasonableness implies that computed depths and velocities are similar to those observed in the field, that the computational effort is notdisproportionate to the rest of the model, and that the precision required for independent parameters is achievable.

A general case surface flow model is developed in the following section and solved for the Manning, Chezy, and laminar flow options. The user must select and possibly modify the surface flow computation to describe surface flow for any particular application.

Nonsteady, Uniform Surface Flow

While nonsteady (time-varying) flow cannot be simultaneously uniform (water surface slope equal to bed slope) because of the finite velocity of small gravity waves, a uniform-flow assumption simplifies analysis and provides a satisfactory description of flow over short reaches where nonsteady changes are gradual. Although numerous conditions of nonuniformity can be seen in shallow runoff over uneven surfaces, uniform flow is often used as an analytic basis since there is rarely a practical way to measure or describe the variety of surface-induced varied flow conditions.

Consider strip of surface, width of W, length L, and slope S. The water surface, also at slope S, is of depth H at the start of a time step. If over a time step dt, there is no additional inflow and a corresponding change of depth dH, the net discharge of fluid from the area is,

$$Q = -WL \frac{dH}{dt} .$$

Because the flow is open channel discharge traveling the surface at velocity V,

$$Q = VWH ,$$

where WH represents the area perpendicular to outflow. Equating the discharges,

$$- WL \frac{dH}{dt} = VWH .$$

As V = f(H), the expression may be expanded. Subsequent derivation will employ the Manning equation although alternative velocity equations may be used.

$$-WL \frac{dH}{dt} = \frac{1.49}{n} H^{2/3} S^{1/2} WH \ .$$

Rearranging terms,

$$-\frac{1.49S^{1/2}}{Ln} dt = H^{-5/3} dH \ .$$

Integrating over a time step Δt in which $dH = H_2 - H_1$,

$$-\frac{1.49 S^{1/2}}{Ln} \int_0^{\Delta t} dt = \int_{H_1}^{H_2} H^{-5/3} dH \ ,$$

or

$$\frac{1.49 S^{1/2} \Delta t}{Ln} = \frac{3}{2} (H_2^{-2/3} - H_1^{-2/3}) \ .$$

As 1.49 ~ 1.5, the equation may be simplified

$$H_2 = \left(\frac{1}{H_1^{2/3}} + \frac{S^{1/2} \Delta t}{Ln} \right)^{-1.5} \ .$$

Had the Chezy equation been used,

$$H_2 = \left(\frac{1}{H_1^{1/2}} + \frac{CS^{1/2} \Delta t}{2L} \right)^{-2} \ .$$

Had the laminar flow been assumed,

$$H_2 = \left(\frac{1}{H_1^2} + \frac{2\Delta t \ g \ S}{3\nu L} \right)^{-1/2} \ .$$

The final depth H_2 varies in positive manner with H_1, L, n and viscosity, and in an inverse manner with Δt, S, and C.

Parameter Estimation

None of the surface flow model formulas is of value if the required parameters cannot be specified. For the watershed model, S is proportional to the mean of the absolute slopes from quadrant midpoint to the midpoints of adjacent quadrants. Field observation indicates that a reasonable factor of proportionality is 1/3. Small cascades or steep chutes account for about twice the elevation drop as does the surface slope. It is this flow along this effective slope that is modeled.

$$S = \left(\frac{1}{4D} \sum \left| E_o - E_x \right|\right)/3 ,$$

where D is quadrant width, E_o is quadrant midpoint elevation and E_x indicates the midpoint elevation of each neighbor. As discussed in the PARTITIONING QUADRANT OUTFLOW section, elevations can be assigned for nonexistent quadrants bounding the watershed boundary.

The surface flow length L can be estimated by stream order analysis, but in general this flow is best estimated by field survey. Locate a local ridge (any place where a falling droplet could start flowing in more than one direction) and trace a steepest-slope descent until evidence of channelized flow is encountered. The average of many such measurements yields L.

H_1 will not be uniform over a quadrant. Simple observation, however, will indicate the relative magnitude of this parameter. As the watershed model adds to or subtracts from this value on a time-step by time-step and quadrant by quadrant basis, H_1 must be established as an initial condition. Since the model is a single event simulation, it will generally be the case that H_1 will be initially at zero.

The time step Δt is an arbitrary value. Because large Δt's induce errors into the sequential routing steps, Δt should be significantly less than the surface travel time L/V.

The laminar flow formula requires a fluid viscosity value which can be obtained from any fluids text and is thermo-dependent. In occasional surface hydrologic studies, severe fluctuations in temperature can lead to measurable changes in runoff behavior.

The Chezy C is generally better established for artificial conduits than land surfaces. It has, however, been related to the Darcy f, Reynold's number, and Nikuradse sand roughness. Thus, there exists ample basis for its theoretical use. Generally it would be preferable to bypass the theory and seek empirical C's from the field.

Manning's n is a somewhat more practical parameter because ample documentation on its estimation exists. Ranges of n are known for varieties of channels and surfaces. It is possible to estimate n by summing weighted contributing factors. Again, it is desirable to calibrate roughness by field work.

Stanford Watershed Model Method

In the Stanford Watershed Model (Crawford and Linsley, 1966), surface flow is computed as follows. The amount of surface detention at equilibrium H_e (ft) is estimated.

$$H_e = 0.000818 \left(\frac{P_i \ nL}{t\sqrt{s}} \right)^{0.6} ,$$

where all terms are as previously defined. P_i/t is rainfall intensity (in./hr) and L is in ft. Surface outflow per ft of width is

$$q_s = \frac{1.49}{n} S^{1/2} \left(\frac{\overline{H}}{L} \right)^{2/3} \left(1 + 0.6 \left(\frac{\overline{H}}{H_e} \right)^3 \right)^{5/3} ,$$

where $\overline{H}$ is average surface storage over the time step. $\overline{H}/H_e$ is assumed to be 1 after rainfall ceases. The computation is appropriate to storms of uniform intensity precipitation but can be modified to simulate runoff from nonuniform rainfall intensity. Approximating,

$$q_s = L(H_1 - H_2)/t$$

for short time steps, q_s can be eliminated,

$$\frac{L(H_1 - H_2)}{t} = \frac{1.49}{n} S^{1/2} \left(\frac{H_1 + H_2}{2L} \right)^{5/3} \left(1 + 0.6 \left(\frac{H_1 + H_2}{2H_e} \right)^3 \right)^{5/3} .$$

This equation may be solved for H_2 by trial-and-error means. Flow velocity is estimated,

$$V = \frac{q_s}{\overline{H}} .$$

Comparison

The following comparison respresents a determination made for a lab study. It is not put forth as a general proof. An early step in any watershed study should be trial calculations and field observation; together, these may indicate a most-reasonable surface flow formula.

In an artificial watershed, precipitation was evenly applied over a sand surface. Surface flow could be observed. Precipitation was applied until steady-state runoff was achieved. Precipitation was then stopped, leaving standing water on the surface; this condition thus, effectively reflects the condition at the start of a time step in the watershed model. Velocities were measured over a short time interval after cessation of rainfall. The following values are representative of experimental runs: $S = 0.02$; $P_t = 5$ in./hr; $H_1 = 0.01$ ft; $t = 5$ sec; $L = 5$ ft; $\nu = 10^{-5}$ ft^2/sec; $C = 65$ (estimated, not back-calculated); $n = 0.025$ (estimated); and $V = 0.6$ fps.

Flow depth H_2 at the end of the time interval can be computed and average velocity estimated by using the mean of H_1 and H_2. Results from the three equations are shown in Table 4.

Both Chezy and Manning reasonably agree with the observed result. The agreement could be improved, however, by better depth and roughness estimates. On the other hand, the laminar model yields a velocity several times greater than that observed and there is little room in that formula for improvement. It is possible that the SWM formulation would better agree with the observed data if the variables had been

Table 4

Depth and Velocity

Equation	H_2	$\overline{V}$
Manning	0.0070	0.35
Chezy	0.0046	0.78
Laminar	0.0044	1.06
SWM	0.0094	0.014
Observed		0.6

more precisely measured. Since the SWM method is slower in computation, however, this option appears to offer little advantage over the simpler models.

It is concluded that preference be given to the Manning equation because it meets the criteria of reasonableness given earlier in this section. Although the Chezy equation has equally good potential, it is less reported in American hydrologic application literature.

CHANNEL FLOW

General

Channel flow is the surface runoff which is confined to discernible watercourses. Channels range from small, temporarily-eroded incisions in the land surface, to large, well-defined rivers and streams. A channel network describes a system of branching channels through which small flows converge into larger flows. In standard hydraulic flood routing, channel networks are described by a sequentially converging pattern of individual channels and in many cases the individual channels are described as a series of reaches.

For quadrant-based watershed modeling, it is not necessary to specify channels individually; rather, the basin topography effectively defines flow direction and confluences.

Any quadrant may receive inflow discharge from zero to three adjacent quadrants and will in turn convey discharge to from one to four neighbors. The network configuration can be deduced from relative quadrant elevations. A partitioning algorithm serves to appropriately divide the outflow achieving, in effect, the result of network delineation without explicitly specifying the directional characteristics of each member of the network. Thus, it is possible to hydraulically route channelized runoff through the watershed on a quadrant-to-quadrant, not reach-to-reach basis. Such routing necessitates a set of hypothetical channel hydraulic characteristics describing a hypothesized channel system which is hydraulically similar to the actual watercourse. Hydraulic computations can then be used to estimate how much water is stored in a quadrant's channel network and how much is released to downstream neighbors.

Quadrant-Based Hypothetical Channels

As discussed in the SURFACE FLOW section, L denotes the average overland surface flow length. Assuming that any channel can draw surface flow equally from both sides, every channel, large or small, directly drains by surface runoff a band of surface 2L wide. Since a quadrant's area is D^2, a hypothetical channel length L_c can be estimated

$$L_c = \frac{D^2}{2L} .$$

This length approximates the total length of all channels within a quadrant. If it is assumed that the hypothetical channels are linear within a quadrant (an assumption better justified if quadrants are small), channels within a quadrant will range in length from 0 to $D\sqrt{2}$. Additional length results if tortuosity or sinuosity is considered. Since this correction does not initially effect the hypothetical channel pattern, it will be applied later.

Channel order in a watershed is a geomorphologic classification scheme in which the most-upstream unbranched tributaries are denoted as first order, channels with only first-order tributaries as second order, those having only first and second-order tributaries as third order, and so on. Various schemes exist by which numbers and lengths of different-ordered channels can be estimated from the order-number of a watershed's main channel (Osterkamp and Hedman, 1977).

Since any quadrant is likely to have channels within it of more than one order, total channel length L_c must be divided into lengths of various orders. The length estimation is simplified by noting that channels within quadrants other than these at watershed boundaries tend to transect, rather than originate in, the quadrant. The average length L of random transections through a D by D quadrant, found by 10,000 random transects, is 0.7066 D. Thus the quadrant has L_c/L or D/(1.4L) hypothetical channels passing through it.

The distribution of these D/(1.4L) channels by order may be estimated by noting that the range of channel orders within a quadrant increases as that quadrant nears to the point of basin outflow. A large proportion of discharge passing through a quadrant near the point of basin outflow is confined to a few high-order channels within that quadrant. Runoff is more evenly distributed over the low-ordered channels within a quadrant far from the point of outflow.

For a given watershed, an arc beyond which principally first-order channels are found may be visualized as radiating from the point of watershed outflow. In many cases this arc radius approaches the distance from the outflow point to the most remote watershed boundary.

arc might define a circular band having few or no channels greater than second order. For the general case, it is not necessary to have discrete bands. Rather, channel order can simply be said to vary in an inverse manner with radial distance from the outflow point. Letting r_i be the distance from the first-order arc and r_u, the radial distance to the first split of the channel of highest order k_u

$$k_r = 1 + (k_u - 1)\left(\frac{r_i - r}{r_i - r_u}\right), \; r_u \leq r \leq r_i ,$$

where k_r indicates the highest channel order at distance r from the outflow point.

Any given quadrant may now be described as having D/(1.4L) channels of order 1 to k_r. It may be further hypothesized (and reasonably verified by examining channel networks) that the distribution of stream lengths by order within a random quadrant is approximately uniform. As the order increases, the average length increases while the count falls. Taking the hypothetical channels to be of mean stream order within the quadrant and assuming a uniform distribution of stream orders, the hypothetical mean stream order is

$$\overline{k} = (k_r + 1)/2 .$$

A reasonably linear correlation exists between the channel order and the log of channel width, w. For the hypothetical channel, if

$$\log(w) = a\overline{k} \ ,$$

where a is a constant of proportionality, then

$$w_r = 10^{a(k_r+1)/2} \ .$$

The constant a may be estimated by measuring the width w_r of the k_r-order outflow channel and back calculating

$$a = \frac{2 \log(w_r)}{(k_r + 1)} \ .$$

For a sixth-order channel, w_u is typically about 10 ft. Thus

$$a = \frac{2 \log(10)}{6 + 1} = \frac{2}{7} \ .$$

Substituting

$$w = 10^{(k_r+1)/7} \ .$$

Because subsequent hydraulics will consider channel cross-sectional geometry and not planar position for intraquadrant routing purposes, the D/(1.4L) hypothetical channels can for intraquadrant routing purposes be considered to be side by side.

Most natural channels are hydraulically wide, having widths many times depth. Surface drag from banks is ignored. Channels that are not wide can be approximated by wide channels by an increase in bed roughness to compensate for the neglected sides. Considering the now-adjacent quadrant channels to be wide, the sides can be removed and the flows united in a common cross section.

The combined width of the hypothetical is

$$w = \frac{D}{1.4L} 10^{(k_r+1)/7} \quad ,$$

which for practical purposes is,

$$w = \frac{D\ 10^{k_r/7}}{L}$$

since $10^{1/7} = 1.39$.

The hypothetical channel is now w wide and 0.7 D long and it is sloped at the mean quadrant slope S. If the channel is tortuous, its actual length is longer by a factor of the tortuosity T and its slope is reduced by this same factor. Thus, the channel is w wide, 0.7 DT long, and sloped S/T.

The volume of outflow from a channel over a time period is

$$d\ Vol = -(\text{surface area})\ dH\ .$$

The change of volume can also be expressed in terms of discharge,

$$d\ Vol = Q\ dt.$$

Using Manning's equation, then

$$-0.7\ DTw\ dH = \frac{1.49}{n} H^{5/3}\ (S/T)^{1/2}\ w \cdot dt\ .$$

Rearranging,

$$- \frac{0.7\ DT^{3/2}\ n}{1.49\ S^{1/2}}\ H^{-5/3}\ dH = dt\ .$$

Integrating over the time step

$$- \frac{0.7\ DT^{3/2}\ n}{1.49\ S^{1/2}} \int_{H_1}^{H_2} H^{-5/3}\ dH = \int_0^{\Delta t} dt$$

or

$$- \frac{0.7\ DT^{3/2}\ n}{1.49\ S^{1/2}} \left(- \frac{3}{2} \left(H_2^{-2/3} - H_1^{-2/3}\right)\right) = \Delta t\ .$$

As 1.49 ≈ 1.5,

$$H_2 = \left(\frac{1}{H_1^{2/3}} + \frac{\Delta t\ s^{1/2}}{0.7\ DT^{3/2}\ n}\right)^{-1/5}\ .$$

Outflow volume over the time step is

$$d\ Vol = 0.7\ DTw(H_1 - H_2)\ .$$

It is this volume that is passed downstream.

Surface

Every quadrant receives runoff inflow from zero to three adjacent quadrants of higher elevation; except for the one identified as the basin discharge, it drains into one to four adjacent quadrants of lower elevation. The outflow partitioning problem involves determining the proportional division of a quadrant's outflow when more than one adjacent quadrant is of lower elevation.

The elevation at any point within a quadrant can be calculated if the quadrant's surface can be mathematicaly described. Such a mathematical definition for this model is an orthogonal parabolic surface: a surface parabolic in both x and y cross section. The parabolic form in either direction can be determined by three points: the midpoint elevations of the left-adjacent quadrant E_L, the center quadrant E_0, and the right-adjacent quadrant E_R for the x or horizontal equation; and the midpoint elevations of the bottom-adjacent quadrant E_B, E_0, and the top-adjacent quadrant E_T for the y or vertical equation.

The elevation at any point along a quadrant's horizontal bisector can be expressed,

$$E(x) = A_x x^2 + B_x x + E_0 \ ,$$

where

$$A_x = \frac{E_L + E_R - 2E_0}{2D^2} \ ,$$

and

$$B_x = \frac{E_R - E_L}{2D} .$$

D is the quadrant width and x is the distance in x direction from quadrant center. Likewise, the elevation at any point along a quadrant's vertical bisector can be expressed

$$E(y) = A_y y^2 + B_y y + E_0 ,$$

where

$$A_y = \frac{E_B + E_T - 2E_0}{2D^2} ,$$

and

$$B_y = \frac{E_T - E_B}{2D} .$$

Vertical distance above the quadrant center is y.

For quadrants with less than four adjacent quadrants, the above equations require one or more assumed adjacent elevations. The assumed values are as follows. When a quadrant is on the right boundary of the basin, no right adjacent quadrant exists. E_R is assumed to be $2E_0 - E_L$. This defines a constant x gradient over the quadrant. Likewise, for a quadrant on the left basin boundary, $E_L = 2E_0 - E_R$. For a quadrant on the bottom basin boundary, $E_B = 2E_0 - E_T$ and for a quadrant at the top basin boundary, $E_T = 2E_0 - E_B$.

If a quadrant lacks adjacent quadrants on both the right and left (or top and bottom) it has no slope in the x (or y) direction. Thus, $E_L = E_R = E_0$ or $E_T = E_B = E_0$.

To this point, elevations have only been specified along the two bisecting axes. Assuming that the orthogonal parabolas are independent of one another, the elevation relative to E_0 of any point x, y in the quadrant may be taken as the net change resulting from x distance along the x axis and y distance along the y axis.

$$E(x,y) = A_x x^2 + B_x x + A_y y^2 + B_y y + E_0$$

This equation describes a surface which has the same parabolic shape along any x-section, the elevation of that shape depending upon the y location of the section. Likewise, the surface will have a fixed parabolic shape along any y-section, the elevation of that shape depending on the x location of the section.

Boundary Continuity

The orthogonal parabolic surface is continuous within a quadrant. The parabolic fit, however, does not generally yield elevations at quadrant boundaries that match those calculated using an adjacent quadrant as a new center quadrant. Such discontinuities could be eliminated by a continuous surface polynomial equation using the mid-point elevation and location of every quadrant in the watershed. However, such an exercise in topology is unnecesary in this case because the parabolically computed quadrant-boundary elevations are never used; only the sign of the component of slope perpendicular to a boundary is considered in partitioning. The sign of the slope must not change when boundaries are crossed or runoff may become mathematically trapped. Boundary sign inconsistency cannot happen in this model.

Boundary sign consistency can be demonstrated from the fact that for any vertically symmetrical parabola, any crest (or valley) between two points lies closer to the higher (lower) point. Taking four points of arbitrary elevations and fitting parabolas through the first and last three, it is seen that midway between the second and third point, the slope of either parabola has the same sign.

If adjacent quadrants have unequal midpoint elevations $E_1 > E_2$, at every point along the common boundary, surface slope from quadrant 1 to quadrant 2 is positive. If $E_1 < E_2$, the slope is negative and if $E_1 = E_2$, the slope is zero.

Slope

Surface slope in the x and y direction at any point x, y is calculated from the first derivative of E(x, y),

$$S(x) = \frac{dE(x)}{dx} = 2A_x x + B_x \ ,$$

and

$$S(y) = \frac{dE(y)}{dy} = 2A_y y + B_y \ .$$

Defining θ to be the angle measured counterclockwise from the x-axis, it can be shown that the direction of the steepest slope at any point is,

$$\theta(x, y) = \arctan(S(y)/S(x)) .$$

As flow must be in the direction of negative slope, the direction of surface runoff at any point on the quadrant is $\theta(x, y) - 180°$. Angle $\theta(x, y)$ is the flowline angle. Since the surface slope perpendicular to $\theta(x, y)$ must be zero, no flow will cross this flowline.

Ridgelines

The parabolic formulations facilitate determination of horizontal and vertical "ridgelines" in a quadrant. Such orthogonal ridgelines correspond not necessarily to mountainous topography, but rather to the x^* that maximizes $E(x)$ and the y^* that maximizes $E(y)$. $E(x)$ is maximized if $dE/dx = 0$ and $A_x < 0$. Setting the x derivative to zero,

$$x^* = \frac{-B_x}{2A_x} .$$

For any x greater than x^*, $S(x)$ will be negative and any water on the surface will flow to the right. For any x less than x^*, $S(x)$ will be positive and any water will flow to the left, if $A_x < 0$, the value of x^* defines a vertical ridgeline, partitioning drainage area between left and right outflow.

Likewise, the divide between outflow to the quadrant above and the quadrant below is

$$y^* = \frac{-B_y}{2A_y},$$

if $A_y < 0$. The A_x or $A_y > 0$ case defines a trough, not a necessary determination in the partitioning problem.

The parabolic form of the section imposes no constraints on x^* and y^*. For the partitioning problem, any meaningful ridgelines are those which lie within or on the quadrant boundaries. If x^* is greater than D/2 (thus placing the computed ridgelines across the quadrant's right boundary), S(x) must be positive over all the quadrant. Any x-axis component of runoff will be to the left. If x^* is less than -D/2, S(x) is negative over all the quadrant. Flow is to the right. If y^* is greater than D/2, S(y) is positive and flow is toward the quadrant below. When y^* is less than -D/2, S(y) is negative and all flow is upward.

Quadrant Partitioning

Given E_0, E_T, E_L, E_B and E_R, it is now possible to calculate E(x, y) and S(x, y), at every point in a quadrant and locate x^* and y^*. Depending upon whether the x and y-profiles are concave, flat, convex or horizontal, and whether x^* and y^* are located within, on, or outside of quadrant boundaries, a variety of resulting surface shapes are possible: hills, saddles, sinks, troughs, planes, etc.

The geometrical shape can be identifed by appraising $\theta(x,y)$ vectors at evenly-spaced intervals over the surface. The magnitudes of

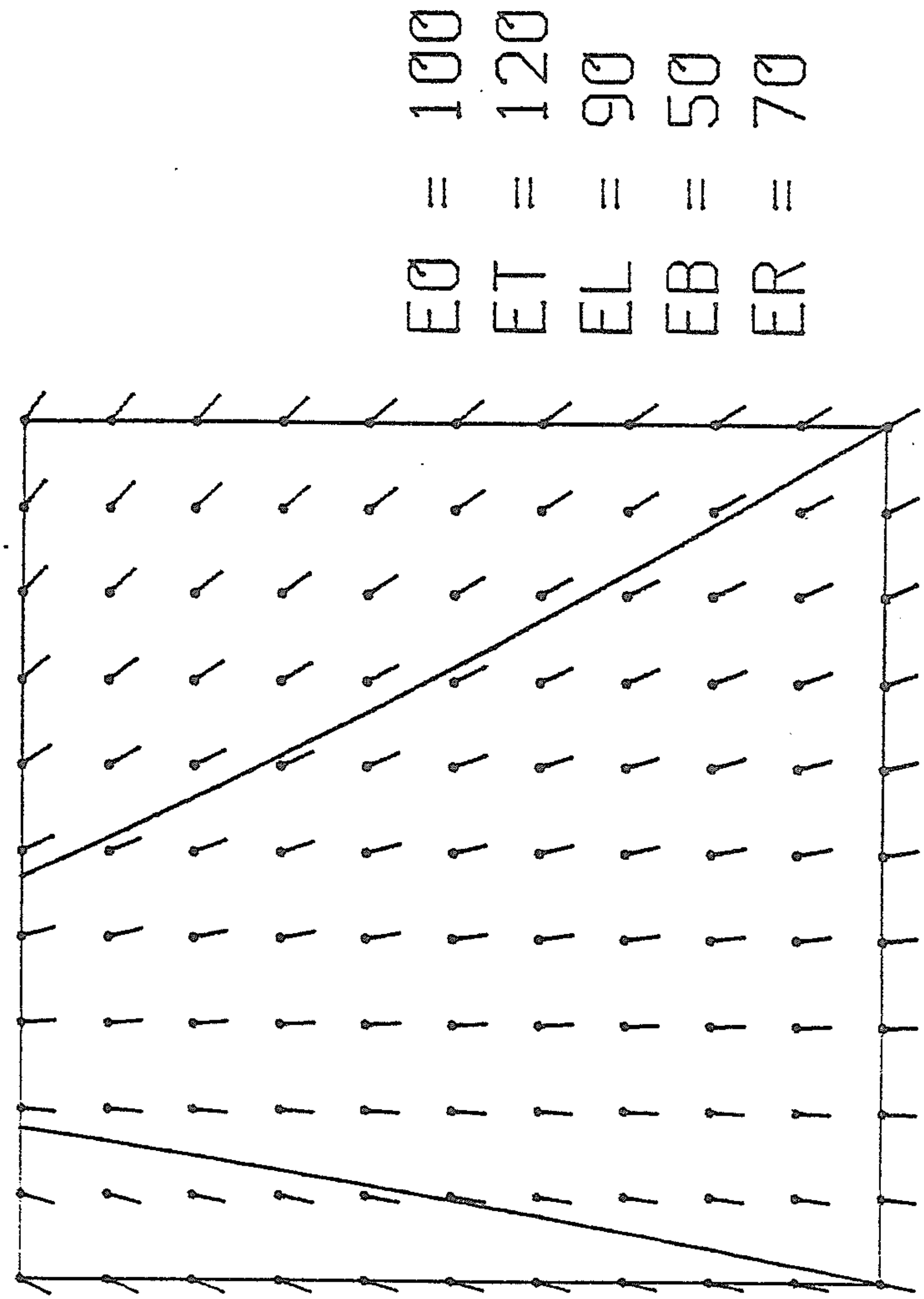

Figure 2. Three-directional partitioning.

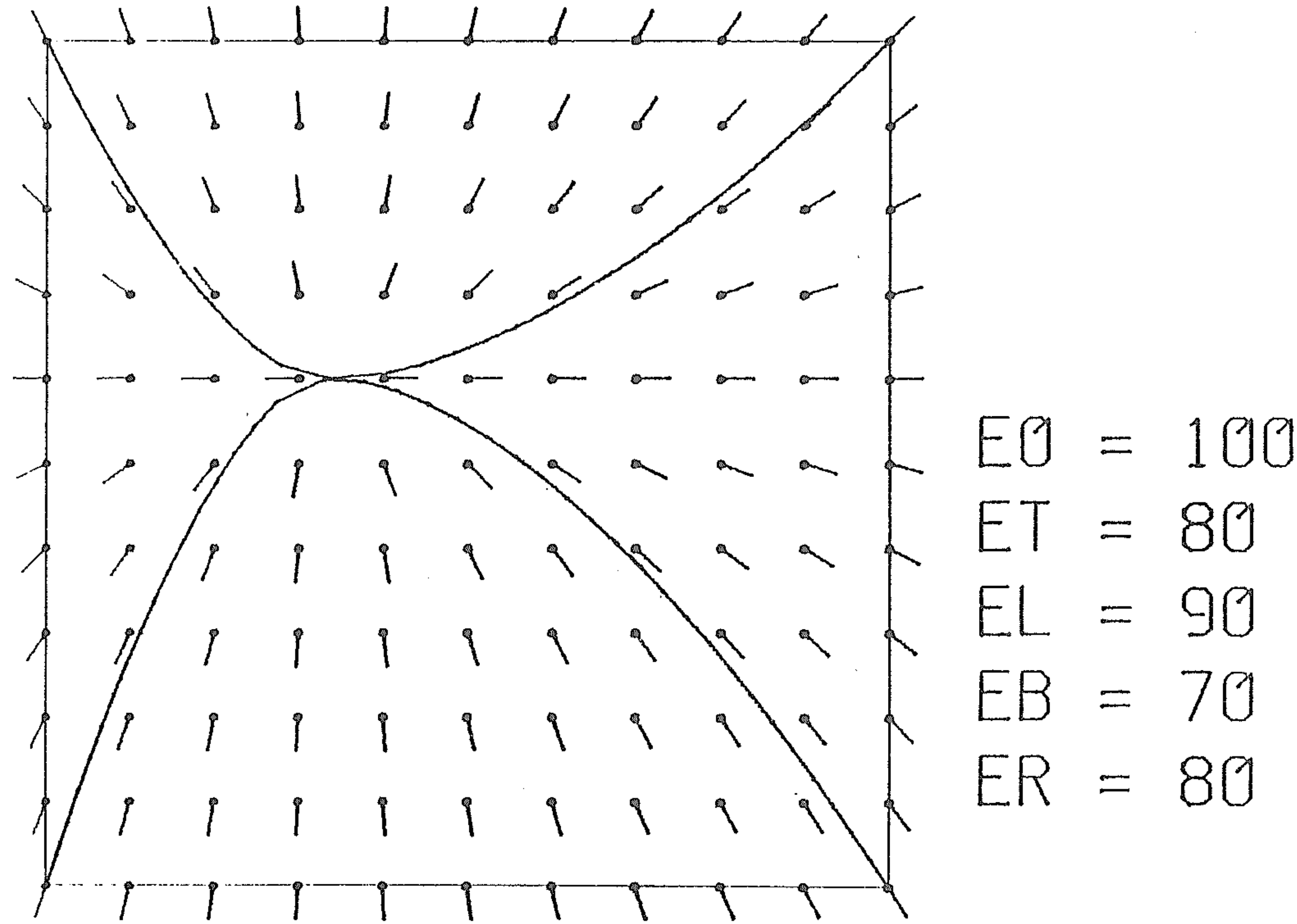

Figure 3. Four-directional partitioning.

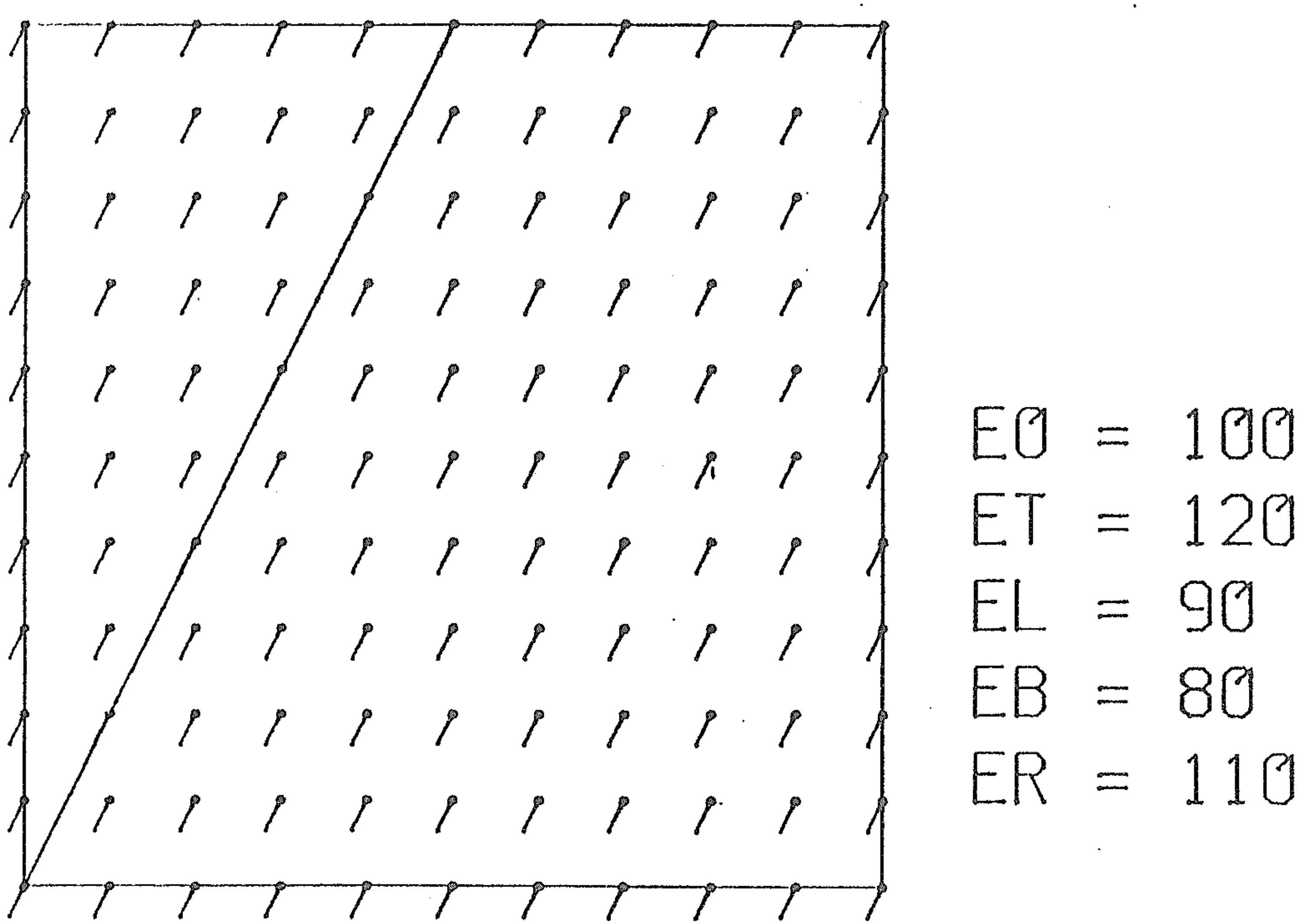

Figure 4. Two-directional partitioning.

S(x,y) and E(x,y) indicate the steepness of the surface, but once θ(x, y) is known, neither E(x,y) nor S(x,y) is needed for partitioning.

Figures 2-4 illustrate θ(x,y) vector patterns for three surfaces. Each vector is rooted by a small circle to its respective x,y coordinate and extends in the steepest downhill direction. Figure 2 illustrates three-directional partitioning due to a ridge downward-sloping toward the bottom of the quadrant. The x* ridgeline exists along the fourth column of vectors from the left, and y* exists above the top edge. Being below the y*, all flow vectors have a downward component. Vectors to the left of x* bend toward the left, and those to the right bend in that direction.

The θ(x,y) can be used to trace a path of a single flowline from any given point. The points of initial interest are the corner points of a quadrant. Flowlines are traced in the uphill direction from each quadrant corner. A small, arbitrary step length is used in direction θ(x,y). At the step length, θ(x,y) is recomputed and another step is taken. The flowline is extended until a quadrant boundary is either crossed or (x*,y*) is reached. Since flow will not cross a flowline, these particular flowlines thus determine the subareas of the quadrant which drain to the four quadrant edges. The area defined by the flowline and an appropriate quadrant corner can be found by the polygon rule.

In Figure 2, flowlines from the bottom corners partition drainage into three areas. Figure 3 is a hill with partitioning to four directions. Both x* and y*, lie within the quadrant. Figure 4 indicates a skewed plane with two-directional partitioning. Since A_x and A_y are both zero, x* and y* do not exist. Note that the y-gradient is twice the x-gradient and both are constant over the entire surface. A quadrant is partitioned by measuring a respective subarea. Values above the slashes in Table 5 summarize the three illustrative figures.

Partitioning is facilitated by computer solution. A general case BASIC partitioning program is listed in the APPENDIX E. The program computes necessary constants (lines 10-130), checks for special case problems where several E's have the same minimum value (140-320), checks for the special saddle case (330-340), assigns quadrant corner coordinates (350-400), develops each corner flowline (410-530), ends the flowline at x*, y* (540-560) or quadrant edge (570-670), determines across which edge that area outflows (680-700), computes the subarea (710-790), recomputes subarea for the special case of a hill (800-850), assigns remaining areas to the appropriate remaining edge (860-900), and prints the result (900-950).

The θ(x,y)-defined surface could be transformed into a contour map if each θ(x,y) were rotated 90° and paths were drawn passing parallel to these new vectors. The elevation of any such path would not be known without evaluating one E(x,y) along the path, but by remaining at zero slope; whatever that elevation was, it would not change along the route.

Table 5

Partitioned Outflow, Vector-Search Method/
Slope-Proportional Method

Figure	Directional Percent			
	Top	Left	Bottom	Right
2	0/0	9.3/11.1	62.8/55.6	27.9/33.3
3	25.6/25	12.1/12.5	38.1/37.5	24.2/25
4	0/0	25/33.3	75/66.7	0/0

A Slope-Proportional Partitioning Alternative

The orthogonal parabolic surface allows runoff partitioning that can be both mathematically programmed and verified by simulated rainfall over any appropriately-shaped impervious surface. While the parabolic assumption may not in general be a good description of large contoured land surfaces, if the land surface is subdivided into sufficiently small quadrants, each quadrant may be parabolically described with reasonable accuracy. Thus orthogonal parabolic partitioning is appropriate for the finite-difference, quadrant-described watershed model.

Unfortunately, the general-case partitioning algorithm is complex. A partitioning algorithm suitable for use as a subroutine called by the main watershed model can be used. The objective of this study, however, was to develop a watershed model reasonably simple in logic, quick to execute, and practical in employment. For this reason, an alternative partitioning method is developed. This method is substantially shorter and in most cases yields watershed runoff results similar to those achieved by the parabolic partitioning.

The alternative partitioning proposed is direct: quadrant outflow is divided in proportion to the magnitude of the negative slopes from the quadrant midpoint to the midpoints of the adjacent quadrants. The four adjacent slopes are

$$S_T = \frac{E_T - E_0}{D} ,$$

$$S_L = \frac{E_L - E_0}{D} ,$$

$$S_B = \frac{E_B - E_0}{D} ,$$

and

$$S_R = \frac{E_R - E_0}{D} .$$

Where a quadrant is on the watershed boundary, artificial adjacent elevations can be estimated in the same linear manner described earlier.

Any $S > 0$ are ignored since outflow cannot travel uphill. Computationally, positive slopes can be ignored by setting them equal to zero. Flow is then partitioned into four subareas,

$$P_T = S_T/\Sigma S ,$$

$$P_L = S_L/\Sigma S ,$$

$$P_B = S_B/\Sigma S ,$$

and

$$P_R = S_R/\Sigma S ,$$

all $S \leq 0$.

This simple slope-proportionality is based on two relaxed assumptions about the surface slope. The first assumption considers partitioning areas between opposite sides. If slope on one side of a quadrant is greater than slope on the opposite quadrant edge (say -4 percent to the left and -2 percent to the right), the quadrant divide (or ridgeline) probably lies nearer the side of milder slope. If, in fact, the surface is parabolic, the divide in this case would be at the third-point. The same result is achieved by the proportional area computation.

The second assumption considers partitioning flow between adjacent edges. If slope to the bottom is -4 percent and slope to the left is -1 percent, in a given time it is assumed that a flowing droplet will travel 4 units downward and 1 unit leftward. This can be verified by doing a force freebody on an object rolling down a skewed plane. The predominant velocity component increases the probability that the traveling droplet will first encounter the bottom edge.

The three surfaces used to illustrate the orthogonal parabolic partitioning can be alternatively partitioned by the slope-proportional method. The results are shown below the slashes in Table 5. Note that although the results are not the same, they are identical in directions and similar in magnitude to the orthogonal parabolic method.

It is suggested that this simpler partitioning alternative be employed for initial watershed simulation. The parabolic method can be substituted if the model is expanded.

PROGRAMMING DISCUSSION

General

The watershed model is written in FORTRAN IV without machine-dependent statements. Three files are required: the data, the program itself, and the output. A compiled program will decrease computer time if multiple runs are anticipated. Since any application may require modification of built-in constants or process equations, the program should be left in source form until results are satisfactory. Total CPU time for compilation and execution of a typical run is approximately 30 seconds on an IBM 30/32.

The program is listed in APPENDIX A. Where language versions allow, the following modifications are suggested: list-directed (free format input); IF-THEN-ELSE constructs to simplify branching; and output file partitioning allowing the user to retrieve results in arbitrary order.

In lieu of increasing the program's length by extensive comment statements, an annotated statement list is given in APPENDIX B. Variable names and units are given in APPENDIX C.

Program Structure

The watershed model can be divided into two segments. The first is a static description of the watershed and the second is a dynamic simulation of the runoff.

Three functions are performed in the static description portion of the program: data input, transformation, and watershed description. The input data, format given APPENDIX D, describes the watershed and storm. Discussion of definitions, limits, and measurement or estimation of input values may be found in the respective topical sections of this report.

Data transformation is required to estimate variables used in subsequent equations. Since many iterated equations employ conglomerate constants, it is computationally advantageous to calculate and save these fixed values. Equations of transformation, other than those simply converting inches to feet, etc., are developed in the respective topical sections.

Watershed description echos the input and provides values for selected transformed variables on a quadrant-by-quadrant basis. Three digital maps are generated. An elevation map shows contour by auto-scaled digits from 0 to 9. A hydrologic soil group map plots soil type and computes percentage composition. Likewise, a cover complex map shows complex code and percentage. The input hyetograph data is returned.

In the simulation segment, watershed state variables are computed and reported at each time step. Precipitation, infiltration, and gaging station discharge as depth are cumulated. Storage and discharge as rate are reported over time.

The simulation segment has two main loops: the outer is incremental time and the inner is the quadrant. Every quadrant is modeled at each time step. Infiltration and storage values are averaged for output. Appropriate interquadrant flows are carried over to the following time step.

Minor program modification could reduce the length of simulation output by supressing, say, all WRITE's not at an even-minute time step.

Graphics

High resolution screen graphics or digital plotting capacity provide a useful summary of output. Unfortunately, either type of plot is machine-dependent and thus cannot be generalized.

For hydrograph and hyetograph illustration in this report, program output was transported to microcomputer disk storage. From there it was reformatted for use in a plotting routine for a flat bed pen plotter.

DEMONSTRATION ANALYSIS

Watershed

Storm water discharge in the Four Hills Arroyo at the southeastern municipal limits of Albuquerque, New Mexico comes from the undeveloped foothills of the Manzano mountains. The drainage area is approximately 750 acres. Elevation difference in the watershed is approximately 800 ft. Channel slopes typically exceed 5 percent and surface slopes may exceed 10 percent. The watershed is shown topographically in Figure 5.

By site survey, the cover complex was estimated to be approximately 60 percent juniper-grass (juniper, pinon, grass, and cholla), 15 percent each mountain-brush (oak brush, mountain mahogany, Apache plume, rabbit brush, skunk brush sumac, cliff rose, and snowberry) and ponderosa pine (timber), and 10 percent herbaceous (grama, tubosa, broom, snakeweed, sagebrush, saltbrush, mesquite, and yucca, with brush the minor element). Overall groundcover was estimated by random transects to be 30 to 40 percent.

Soil types, shown in Figure 6, in the watershed are approximately 15 percent rock outcrop--Orthids complex having slopes exceeding 40 percent, and 80 percent Tesajo-Millet stony, sandy loam having slopes less than 10 percent. Minor zones of Salas complex, a gravely and stoney loam as well as Embudo, gravely, fine sandy loam are also found. All four hydrologic soil groups, A, B, C, and D are encountered in the watershed. Groups A, B, and D occur in approximately equal portions. Group C is negligible (U.S. SCS, 1977).

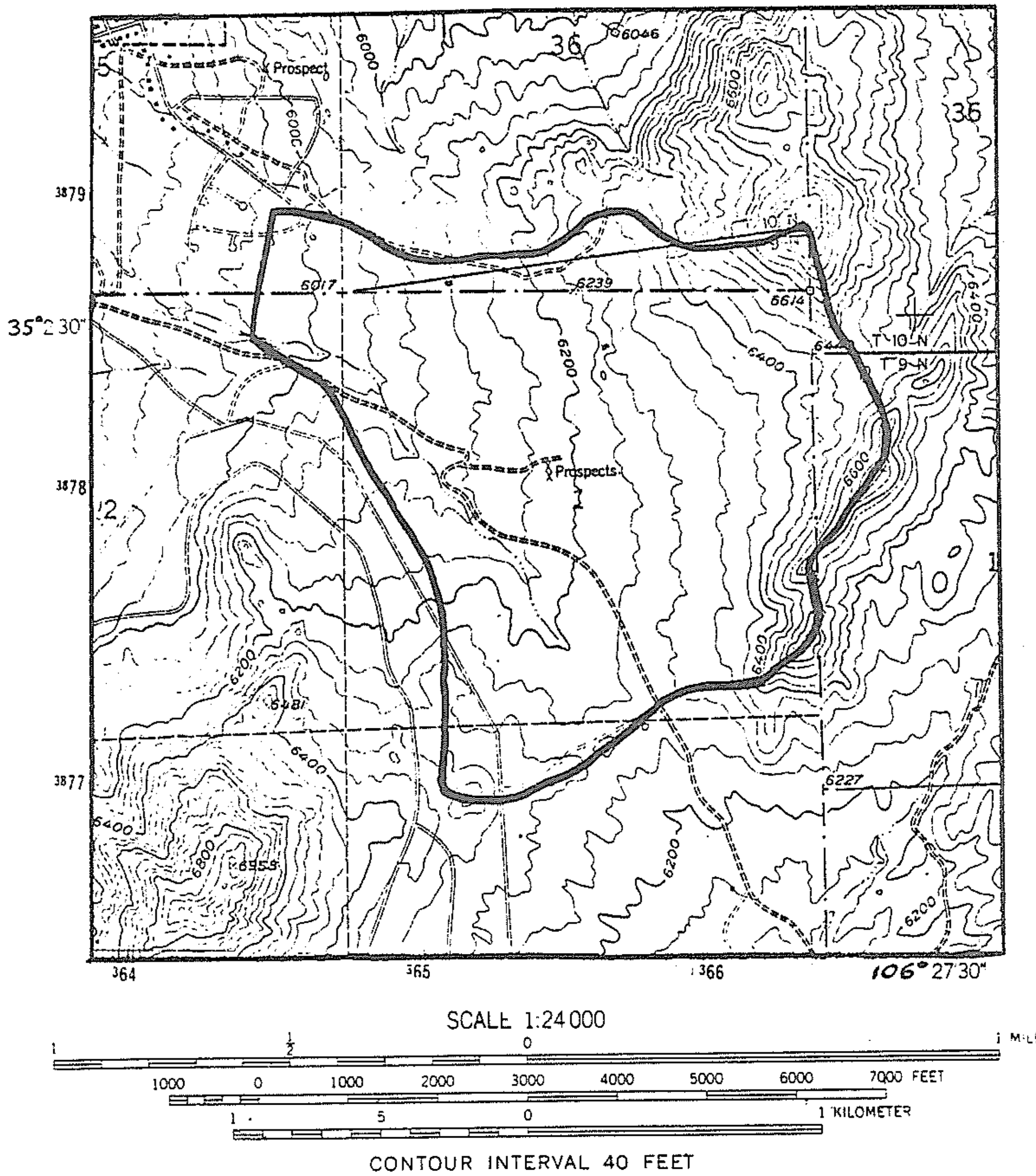

Figure 5. Topography, Four Hills.

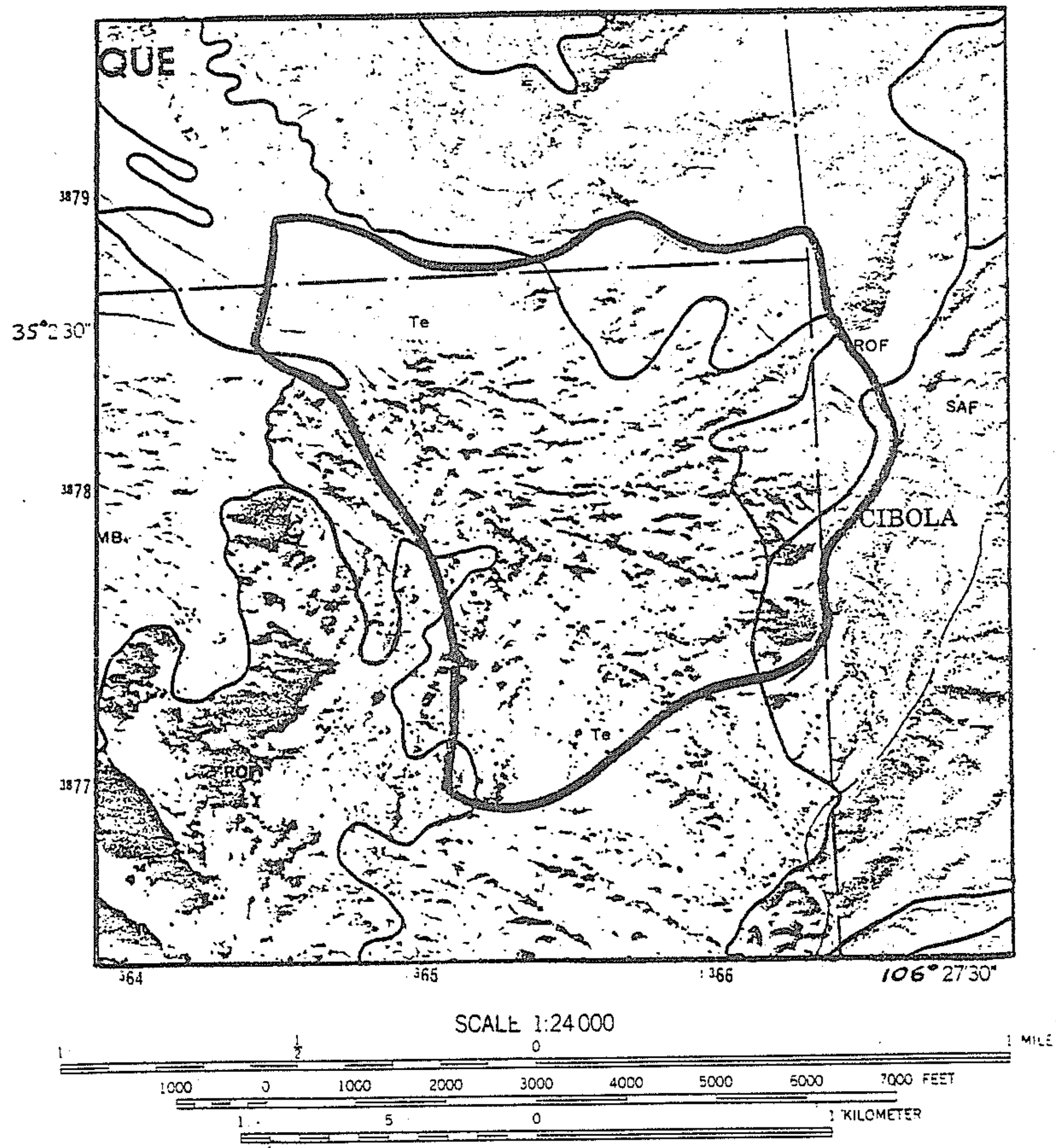

Figure 6. Soil, Four Hills.

Ephemeral channels are well defined with course sand beds. Channels have a sinuousity of roughly 1.5. Manning's roughness for channel beds is roughly 0.06; the beds are generally clean in the center with brushy banks flooded less than annually.

An antecedent moisture condition 2 (average conditions preceeding maximum annual floods) was assumed.

Precipitation

To select the proper design storm, times of concentration were estimated by the following methods: slope and cover-dependent velocities, average slope nomograph, and the Kirpech formula. Forty to forty-five minute concentration times resulted. A 1 hr storm was employed for analysis, the minimum deviation established by local design policy.

From precipitation-frequency maps, the following 100-year rainfall was synthesized: 5 minute intensities of 2.16, 4.11, 7.44, 3.08, 1.91, 1.56, 1.32, 1.20, 1.20, 0.60, 0.60, and 0.60 in/hr (NOAA, 1973). The time distribution reflects the tendency of thunderstorms in New Mexico to have maximum intensity at approximately 15 minutes after initiation. Hourly total rainfall is 2.15 inches.

Data Input

The input data is listed in Figure 7. This data should be submitted as a file, as interactive entry would be prohibitively repetitious were the program to be rerun several times. Line numbers are

```
FOUR HILLS WATERSHED
2.          80.        1.6          .06     500.     2000.     5000.     9
      2      8  6560D   PP   .3
      2      9  6600D   JG   .3
      3      6  6520D   JG   .3
      3      7  6450D   PP   .3
      3      8  6450D   JG   .3
      3      9  6450D   PP   .3
      3     10  6500D   PP   .3
      3     11  6600D   PP   .3
      4      4  6800D   PP   .3
      4      5  6600D   JG   .3
      4      6  6480D   PP   .3
      4      7  6420A   JG   .3
      4      8  6390B   PP   .3
      4      9  6380D   JG   .3
      4     10  6380D   PP   .3
      4     11  6400D   JG   .3
      4     12  6420D   PP   .3
      4     13  6480D   JG   .3
      5      5  6500D   PP   .3
      5      6  6440D   JG   .3
      5      7  6380D   PP   .3
      5      8  6340A   JG   .3
      5      9  6330D   PP   .3
      5     10  6330D   JG   .3
      5     11  6340B   PP   .3
      5     12  6330A   JG   .3
      5     13  6340B   PP   .3
      5     14  6340C   JG   .3
      6      5  6420D   JG   .3
      6      6  6370D   JG   .3
      6      7  6340A   JG   .3
      6      8  6310B   JG   .3
      6      9  6300A   JG   .4
      6     10  6290B   JG   .4
      6     11  6290A   JG   .4
      6     12  6290B   JG   .4
      6     13  6290A   JG   .4
      6     14  6290B   PP   .4
      7      4  6350D   PP   .3
      7      5  6320D   JG   .3
      7      6  6320D   MB   .3
      7      7  6300B   JG   .3
      7      8  6280A   JG   .4
      7      9  6260B   MB   .4
      7     10  6250A   JG   .4
      7     11  6250B   JG   .4
      7     12  6250A   MB   .4
```

Figure 7. Input.

50	7	13	6260B	JG	.4
51	7	14	6260A	JG	.4
52	8	3	6310D	JG	.3
53	8	4	6300D	JG	.3
54	8	5	6280D	MB	.3
55	8	6	6250D	JG	.4
56	8	7	6240D	JG	.4
57	8	8	6230B	MB	.4
58	8	9	6220A	JG	.4
59	8	10	6210B	JG	.4
60	8	11	6210A	MB	.4
61	8	12	6220B	JG	.4
62	8	13	6220A	JG	.4
63	8	14	6230B	JG	.4
64	8	15	6250A	PP	.4
65	9	3	6260D	JG	.4
66	9	4	6240D	MB	.3
67	9	5	6230D	JG	.3
68	9	6	6200D	JG	.4
69	9	7	6180B	MB	.4
70	9	8	6180A	JG	.4
71	9	9	6180B	JG	.4
72	9	10	6180A	MB	.4
73	9	11	6180B	JG	.4
74	9	12	6190A	JG	.4
75	9	13	6200B	MB	.4
76	9	14	6220A	JG	.4
77	9	15	6240B	JG	.4
78	9	16	6280A	MB	.4
79	10	3	6200D	MB	.3
80	10	4	6190D	JG	.3
81	10	5	6180A	JG	.4
82	10	6	6170B	MB	.4
83	10	7	6150A	JG	.4
84	10	8	6140B	JG	.4
85	10	9	6140A	MB	.4
86	10	10	6150B	JG	.4
87	10	11	6150A	JG	.4
88	10	12	6180B	MB	.4
89	10	13	6200A	JG	.4
90	10	14	6230B	JG	.4
91	10	15	6280A	MB	.4
92	10	16	6300B	JG	.4
93	11	4	6140D	JG	.4
94	11	5	6130B	MB	.4
95	11	6	6130A	JG	.4
96	11	7	6120B	JG	.4
97	11	8	6110A	MB	.4
98	11	9	6110B	JG	.4
99	11	10	6120A	JG	.4
100	11	11	6140B	MB	.4

Figure 7. (continued).

101	11	12	6190D	JG	.4
102	11	13	6240D	JG	.4
103	11	14	6270A	MB	.4
104	11	15	6290B	JG	.4
105	11	16	6320D	JG	.4
106	12	3	6090D	H	.4
107	12	4	6100D	JG	.4
108	12	5	6090A	JG	.4
109	12	6	6090B	H	.4
110	12	7	6080A	JG	.4
111	12	8	6080B	JG	.4
112	12	9	6090A	H	.4
113	12	10	6120B	JG	.4
114	12	11	6140A	JG	.4
115	13	3	6040D	JG	.4
116	13	4	6050A	JG	.4
117	13	5	6050B	H	.4
118	13	6	6040A	JG	.4
119	13	7	6040B	JG	.4
120	13	8	6060A	H	.4
121	13	9	6090B	JG	.4
122	14	2	6030D	JG	.4
123	14	3	6010D	JG	.4
124	14	4	6020B	H	.4
125	14	5	6010A	JG	.4
126	14	6	6000B	JG	.4
127	14	7	6010A	H	.4
128	15	2	5995A	JG	.4
129	15	3	5990B	H	.4
130	15	4	5985A	JG	.4
131	15	5	5980B	JG	.4
132	15	6	5990A	H	.4
133	16	5			
134	.25	90.0			
135	0.	2.16			
136	5.	4.11			
137	10.	7.44			
138	15.	3.08			
139	20.	1.92			
140	25.	1.56			
141	30.	1.32			
142	35.	1.20			
143	45.	0.60			
144	60.	0.			
145					

Figure 7. (continued).

included in the file for reference only. Column 1 contains the F in the first line. Note that this line is wrapped to fit on the page. Format fields are described in APPENDIX D. Since 131 of the 145 lines are quadrant descriptions, it is suggested that a preprocessing tabbing routine be used to properly space these variables.

Program Output

The program output is listed in Figure 8. Note that in the quadrant description, the transformed variables AS and CN,...,W are given. These values, should be confirmed by field study. If unrealistic numbers appear to be generated, there is evidence that constants in the generating functions should be modified.

The three maps produced provide a visual check on the input data. The maps may be distorted in planar perspective by the printer's aspect ratio. If on certain printers the distortion seems excessive, a FORMAT change may be called for.

The hydrologic simulation output is largely self-explanatory. After a simulation run, the cumulative totals should be compared for reasonable proportions and rate constants adjusted as required. An illustration of this correction is that of surface and channel infiltration. An initial run with this data, using a literature estimation of channel loss, indicated that channel seepage accounted for less than 1 percent of surface infiltration. Observation indicates that channel infiltration is much more significant; arroyos often decrease flow in

QUADRANT DATA FOR FOUR HILLS WATERSHED

ANTECEDENT MOISTURE CONDITION 2.

OVERLAND TRAVEL LENGTH = 80.00 FT

CHANNEL SINUOSITY FACTOR = 1.60

CHANNEL ROUGHNESS = 0.060

ROW	COL	ELEV	AS	SG	CG	PCTC	CN	FI	FMAX	UN	W
2	8	6560.00	0.1500	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
2	9	6600.00	0.1900	D	JG	0.30	90.0	0.42	1.11	0.130	8.68
3	6	6520.00	0.1100	D	JG	0.30	90.0	0.42	1.11	0.130	8.68
3	7	6450.00	0.0650	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
3	8	6450.00	0.0850	D	JG	0.30	90.0	0.42	1.11	0.130	8.68
3	9	6450.00	0.1350	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
3	10	6500.00	0.1950	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
3	11	6600.00	0.3000	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
4	4	6800.00	0.4000	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
4	5	6600.00	0.2600	D	JG	0.30	90.0	0.42	1.11	0.130	8.68
4	6	6480.00	0.1300	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
4	7	6420.00	0.0800	A	JG	0.30	57.2	2.30	7.48	0.130	8.68
4	8	6390.00	0.0750	B	PP	0.30	63.4	1.44	5.77	0.130	8.68
4	9	6380.00	0.0650	D	JG	0.30	90.0	0.42	1.11	0.130	8.68
4	10	6380.00	0.0950	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
4	11	6400.00	0.1500	D	JG	0.30	90.0	0.42	1.11	0.130	8.68
4	12	6420.00	0.1300	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
4	13	6480.00	0.2000	D	JG	0.30	90.0	0.42	1.11	0.130	8.68
5	5	6500.00	0.1500	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
5	6	6440.00	0.1150	D	JG	0.30	90.0	0.42	1.11	0.130	8.68
5	7	6380.00	0.0900	D	PP	0.30	84.2	0.42	1.88	0.130	8.68
5	8	6340.00	0.0650	A	JG	0.30	57.2	2.30	7.48	0.130	8.68
5	9	6330.00	0.0450	D	PP	0.30	84.2	0.42	1.88	0.149	8.68
5	10	6330.00	0.0500	D	JG	0.30	90.0	0.42	1.11	0.149	8.68
5	11	6340.00	0.0650	B	PP	0.30	63.4	1.44	5.77	0.130	8.68
5	12	6330.00	0.0750	A	JG	0.30	57.2	2.30	7.48	0.130	8.68
5	13	6340.00	0.1000	B	PP	0.30	63.4	1.44	5.77	0.130	8.68
5	14	6340.00	0.0500	C	JG	0.30	79.8	0.85	2.53	0.149	8.68
6	5	6420.00	0.1400	D	JG	0.30	90.0	0.42	1.11	0.130	8.68
6	6	6370.00	0.1000	D	JG	0.30	90.0	0.42	1.11	0.130	8.68
6	7	6340.00	0.0700	A	JG	0.30	57.2	2.30	7.48	0.130	8.68
6	8	6310.00	0.0500	B	JG	0.30	68.4	1.44	4.62	0.149	8.68
6	9	6300.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	8.68
6	10	6290.00	0.0450	B	JG	0.40	63.2	1.52	5.82	0.161	8.68
6	11	6290.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	8.68

Figure 8. Output.

6	12	6290.00	0.0400	B	JG	0.40	63.2	1.52	5.82	0.161	8.68
6	13	6290.00	0.0400	A	JG	0.40	50.6	2.40	9.76	0.161	8.68
6	14	6290.00	0.0400	B	PP	0.40	60.2	1.52	6.61	0.161	8.68
7	4	6350.00	0.0800	D	PP	0.30	84.2	0.42	1.88	0.130	13.14
7	5	6320.00	0.0850	D	JG	0.30	90.0	0.42	1.11	0.130	13.47
7	6	6320.00	0.0700	D	MB	0.30	87.6	0.42	1.42	0.130	13.14
7	7	6300.00	0.0700	B	JG	0.30	68.4	1.44	4.62	0.130	12.23
7	8	6280.00	0.0600	A	JG	0.40	50.6	2.40	9.76	0.140	10.88
7	9	6260.00	0.0550	B	MB	0.40	64.6	1.52	5.48	0.161	9.28
7	10	6250.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	8.68
7	11	6250.00	0.0400	B	JG	0.40	63.2	1.52	5.82	0.161	8.68
7	12	6250.00	0.0400	A	MB	0.40	52.8	2.40	8.94	0.161	8.68
7	13	6260.00	0.0400	B	JG	0.40	63.2	1.52	5.82	0.161	8.68
7	14	6260.00	0.0300	A	JG	0.40	50.6	2.40	9.76	0.161	8.68
8	3	6310.00	0.0600	D	JG	0.30	90.0	0.42	1.11	0.130	18.74
8	4	6300.00	0.0700	D	JG	0.30	90.0	0.42	1.11	0.130	20.32
8	5	6280.00	0.0700	D	MB	0.30	87.6	0.42	1.42	0.130	20.88
8	6	6250.00	0.0800	D	JG	0.40	89.0	0.46	1.24	0.140	20.32
8	7	6240.00	0.0700	D	JG	0.40	89.0	0.46	1.24	0.140	18.74
8	8	6230.00	0.0600	B	MB	0.40	64.6	1.52	5.48	0.140	16.45
8	9	6220.00	0.0500	A	JG	0.40	50.6	2.40	9.76	0.161	13.80
8	10	6210.00	0.0400	B	JG	0.40	63.2	1.52	5.82	0.161	11.13
8	11	6210.00	0.0400	A	MB	0.40	52.8	2.40	8.94	0.161	8.68
8	12	6220.00	0.0350	B	JG	0.40	63.2	1.52	5.82	0.161	8.68
8	13	6220.00	0.0350	A	JG	0.40	50.6	2.40	9.76	0.161	8.68
8	14	6230.00	0.0350	B	JG	0.40	63.2	1.52	5.82	0.161	8.68
8	15	6250.00	0.0300	A	PP	0.40	49.8	2.40	10.08	0.161	8.68
9	3	6260.00	0.0750	D	JG	0.40	89.0	0.46	1.24	0.140	28.63
9	4	6240.00	0.0700	D	MB	0.30	87.6	0.42	1.42	0.130	31.38
9	5	6230.00	0.0700	D	JG	0.30	90.0	0.42	1.11	0.130	32.37
9	6	6200.00	0.0650	D	JG	0.40	89.0	0.46	1.24	0.140	31.38
9	7	6180.00	0.0550	B	MB	0.40	64.6	1.52	5.48	0.161	28.63
9	8	6180.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	24.71
9	9	6180.00	0.0400	B	JG	0.40	63.2	1.52	5.82	0.161	20.32
9	10	6180.00	0.0300	A	MB	0.40	52.8	2.40	8.94	0.161	16.03
9	11	6180.00	0.0350	B	JG	0.40	63.2	1.52	5.82	0.161	12.23
9	12	6190.00	0.0300	A	JG	0.40	50.6	2.40	9.76	0.161	9.08
9	13	6200.00	0.0250	B	MB	0.40	64.6	1.52	5.48	0.182	8.68
9	14	6220.00	0.0300	A	JG	0.40	50.6	2.40	9.76	0.161	8.68
9	15	6240.00	0.0550	B	JG	0.40	63.2	1.52	5.82	0.161	8.68
9	16	6280.00	0.0600	A	MB	0.40	52.8	2.40	8.94	0.140	8.68
10	3	6200.00	0.0700	D	MB	0.30	87.6	0.42	1.42	0.130	43.53
10	4	6190.00	0.0600	D	JG	0.30	90.0	0.42	1.11	0.130	48.40
10	5	6180.00	0.0600	A	JG	0.40	50.6	2.40	9.76	0.140	50.19
10	6	6170.00	0.0500	B	MB	0.40	64.6	1.52	5.48	0.161	48.40
10	7	6150.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	43.53
10	8	6140.00	0.0400	B	JG	0.40	63.2	1.52	5.82	0.161	36.79
10	9	6140.00	0.0400	A	MB	0.40	52.8	2.40	8.94	0.161	29.51
10	10	6150.00	0.0350	B	JG	0.40	63.2	1.52	5.82	0.161	22.69

Figure 8. (continued).

10	11	6150.00	0.0350	A	JG	0.40	50.6	2.40	9.76	0.161	16.88
10	12	6180.00	0.0350	B	MB	0.40	64.6	1.52	5.48	0.161	12.23
10	13	6200.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	8.68
10	14	6230.00	0.0650	B	JG	0.40	63.2	1.52	5.82	0.140	8.68
10	15	6280.00	0.0600	A	MB	0.40	52.8	2.40	8.94	0.140	8.68
10	16	6300.00	0.0400	B	JG	0.40	63.2	1.52	5.82	0.161	8.68
11	4	6140.00	0.0550	D	JG	0.40	89.0	0.46	1.24	0.161	74.52
11	5	6130.00	0.0500	B	MB	0.40	64.6	1.52	5.48	0.161	77.82
11	6	6130.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	74.52
11	7	6120.00	0.0450	B	JG	0.40	63.2	1.52	5.82	0.161	65.73
11	8	6110.00	0.0350	A	MB	0.40	52.8	2.40	8.94	0.161	54.06
11	9	6110.00	0.0300	B	JG	0.40	63.2	1.52	5.82	0.161	42.06
11	10	6120.00	0.0300	A	JG	0.40	50.6	2.40	9.76	0.161	31.38
11	11	6140.00	0.0400	B	MB	0.40	64.6	1.52	5.48	0.161	22.69
11	12	6190.00	0.0600	D	JG	0.40	89.0	0.46	1.24	0.140	16.03
11	13	6240.00	0.0800	D	JG	0.40	89.0	0.46	1.24	0.140	11.13
11	14	6270.00	0.0650	A	MB	0.40	52.8	2.40	8.94	0.140	8.68
11	15	6290.00	0.0350	B	JG	0.40	63.2	1.52	5.82	0.161	8.68
11	16	6320.00	0.0500	D	JG	0.40	89.0	0.46	1.24	0.161	8.68
12	3	6090.00	0.0600	D	H	0.40	89.0	0.46	1.24	0.140	98.10
12	4	6100.00	0.0550	D	JG	0.40	89.0	0.46	1.24	0.161	114.33
12	5	6090.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	120.67
12	6	6090.00	0.0500	B	H	0.40	73.6	1.52	3.59	0.161	114.33
12	7	6080.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	98.10
12	8	6080.00	0.0300	B	JG	0.40	63.2	1.52	5.82	0.161	77.82
12	9	6090.00	0.0300	A	H	0.40	62.6	2.40	5.97	0.161	58.34
12	10	6120.00	0.0250	B	JG	0.40	63.2	1.52	5.82	0.182	42.06
12	11	6140.00	0.0200	A	JG	0.40	50.6	2.40	9.76	0.182	29.51
13	3	6040.00	0.0500	D	JG	0.40	89.0	0.46	1.24	0.161	120.67
13	4	6050.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	120.67
13	5	6050.00	0.0450	B	H	0.40	73.6	1.52	3.59	0.161	120.67
13	6	6040.00	0.0500	A	JG	0.40	50.6	2.40	9.76	0.161	120.67
13	7	6040.00	0.0450	B	JG	0.40	63.2	1.52	5.82	0.161	120.67
13	8	6060.00	0.0450	A	H	0.40	62.6	2.40	5.97	0.161	108.49
13	9	6090.00	0.0300	B	JG	0.40	63.2	1.52	5.82	0.161	77.82
14	2	6030.00	0.0550	D	JG	0.40	89.0	0.46	1.24	0.161	120.67
14	3	6010.00	0.0400	D	JG	0.40	89.0	0.46	1.24	0.161	120.67
14	4	6020.00	0.0425	B	H	0.40	73.6	1.52	3.59	0.161	120.67
14	5	6010.00	0.0450	A	JG	0.40	50.6	2.40	9.76	0.161	120.67
14	6	6000.00	0.0350	B	JG	0.40	63.2	1.52	5.82	0.161	120.67
14	7	6010.00	0.0400	A	H	0.40	62.6	2.40	5.97	0.161	120.67
15	2	5995.00	0.0400	A	JG	0.40	50.6	2.40	9.76	0.161	120.67
15	3	5990.00	0.0250	B	H	0.40	73.6	1.52	3.59	0.182	120.67
15	4	5985.00	0.0400	A	JG	0.40	50.6	2.40	9.76	0.161	120.67
15	5	5980.00	0.0375	B	JG	0.40	63.2	1.52	5.82	0.161	120.67
15	6	5990.00	0.0200	A	H	0.40	62.6	2.40	5.97	0.182	120.67

DISCHARGE FROM QUADRANT (15, 5) TO QUADRANT (16, 5)

Figure 8. (continued).

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
2 *							7	7							
3 *					6	5	5	5	6	7					
4 *			9	7	6	5	4	4	4	5	5	6			
5 *				6	5	4	4	4	4	4	4	4	4		
6 *				5	4	4	4	3	3	3	3	3	3		
7 *			4	4	4	3	3	3	3	3	3	3	3		
8 *		4	3	3	3	3	3	2	2	2	2	2	3	3	
9 *		3	3	3	2	2	2	2	2	2	2	2	2	3	3
10 *		2	2	2	2	2	1	1	2	2	2	2	3	3	3
11 *			1	1	1	1	1	1	1	1	2	3	3	3	4
12 *		1	1	1	1	1	1	1	1	1					
13 *		C	0	C	0	0	0	1							
14 *	0	C	0	0	0	0									
15 *	0	C	0	0	0										
	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

ELEVATICN MAF CF FCUR HILLS WATERSHEC

AREA = 746.10 ACRES   QUAD WIDTH = 5CC.CO FT

EMAX = 6600.CO FT   EMIN = 5980.0C AT (15, 5)

CONTCUR INTERVAL = 91.11 FT

Figure 8. (continued).

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
2 *							D	D							
3 *					D	C	D	D	D	D					
4 *			D	C	D	A	B	C	D	C	D	D			
5 *				C	D	D	A	D	D	B	A	B	C		
6 *				D	D	A	B	A	B	A	B	A	B		
7 *			D	D	D	B	A	B	A	B	A	B	A		
8 *		C	D	C	D	C	B	A	B	A	B	A	B	A	
9 *		C	C	D	D	B	A	B	A	B	A	B	A	B	A
10 *		C	D	A	B	A	B	A	B	A	B	A	B	A	B
11 *			D	B	A	B	A	B	A	B	D	D	A	B	D
12 *		C	D	A	B	A	B	A	B	A					
13 *		C	A	B	A	B	A	B							
14 *	D	C	B	A	B	A									
15 *	A	B	A	B	A										
	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

HYDROLOGIC SOIL GROUP MAP OF FOUR HILLS WATERSHED

QUAD WIDTH = 500.00 FT

PERCENT SOIL GROUP A = 32.31
PERCENT SOIL GROUP B = 31.54
PERCENT SOIL GROUP C = 0.77
PERCENT SOIL GROUP D = 35.38

Figure 8. (continued).

2 *							PP	JG							
3 *					JG	PP	JG	PP	PP	PP					
4 *			PP	JG	PP	JG	PP	JG	PP	JG	PP	JG			
5 *				PP	JG	PP	JG	PP	JG	PP	JG	PP	JG		
6 *				JG	JG	JG	JG	JG	JG	JG	JG	JG	PP		
7 *			PP	JG	MB	JG	JG	MB	JG	JG	MB	JG	JG		
8 *		JG	JG	MB	JG	JG	MB	JG	JG	MB	JG	JG	JG	PP	
9 *		JG	MB	JG	JG	MB	JG	JG	MB	JG	JG	MB	JG	JG	MB
10 *		MB	JG	JG	MB	JG	JG	MB	JG	JG	MB	JG	JG	MB	JG
11 *			JG	MB	JG	JG	MB	JG	JG	MB	JG	JG	MB	JG	JG
12 *		H	JG	JG	H	JG	JG	H	JG	JG					
13 *		JG	JG	H	JG	JG	H	JG							
14 *	JG	JG	H	JG	JG	H									
15 *	JG	H	JG	JG	H										
	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

COVER COMPLEX MAP OF FOUR HILLS WATERSHED

QUAD WIDTH = 500.00 FT

COVER COMPLEX CE = 0.0
COVER COMPLEX H = 6.92
COVER COMPLEX MB = 15.38
COVER COMPLEX JG = 63.85
COVER COMPLEX PP = 13.85

Figure 8. (continued).

PRECIPITATION INPUT TO FOUR HILLS WATERSHED

TIME (MIN)	INTENSITY (IN/HR)
0.0	2.16
5.00	4.11
10.00	7.44
15.00	3.08
20.00	1.92
25.00	1.56
30.00	1.32
35.00	1.20
45.00	0.60
60.00	0.0

HYDROLOGIC SIMULATION OF FOUR HILLS WATERSHED

PERIOD	TIME (MIN)	PRECIPITATION INTENSITY (IN/HR)	PRECIPITATION INPUT (IN)	PRECIPITATION TOTAL (IN)	INFILTRATION SURFACE (IN)	INFILTRATION CHANNEL (IN)	STORAGE SURFACE (IN)	STORAGE CHANNEL (IN)	DISCHARGE TOTAL (IN)	DISCHARGE RATE (CFS)
1	0.0	2.1600	0.0090	0.0090	0.0056	0.0000	0.0034	0.0	0.0	0.0
2	0.25	2.1600	0.0090	0.0180	0.0111	0.0000	0.0069	0.0000	0.0000	0.00
3	0.50	2.1600	0.0090	0.0270	0.0167	0.0000	0.0103	0.0000	0.0000	0.00
4	0.75	2.1600	0.0090	0.0360	0.0222	0.0000	0.0136	0.0001	0.0000	0.00
5	1.00	2.1600	0.0090	0.0450	0.0277	0.0000	0.0170	0.0001	0.0000	0.00
6	1.25	2.1600	0.0090	0.0540	0.0333	0.0001	0.0203	0.0002	0.0000	0.00
7	1.50	2.1600	0.0090	0.0630	0.0388	0.0001	0.0236	0.0003	0.0000	0.00
8	1.75	2.1600	0.0090	0.0720	0.0443	0.0001	0.0268	0.0005	0.0000	0.00
9	2.00	2.1600	0.0090	0.0810	0.0499	0.0001	0.0300	0.0007	0.0000	0.00
10	2.25	2.1600	0.0090	0.0900	0.0554	0.0002	0.0332	0.0010	0.0000	0.00
11	2.50	2.1600	0.0090	0.0990	0.0609	0.0002	0.0363	0.0013	0.0000	0.00
12	2.75	2.1600	0.0090	0.1080	0.0664	0.0003	0.0393	0.0016	0.0000	0.00
13	3.00	2.1600	0.0090	0.1170	0.0719	0.0003	0.0423	0.0020	0.0000	0.00
14	3.25	2.1600	0.0090	0.1260	0.0775	0.0004	0.0453	0.0024	0.0000	0.00
15	3.50	2.1600	0.0090	0.1350	0.0830	0.0004	0.0481	0.0029	0.0000	0.00
16	3.75	2.1600	0.0090	0.1440	0.0885	0.0005	0.0510	0.0034	0.0000	0.00
17	4.00	2.1600	0.0090	0.1530	0.0940	0.0006	0.0538	0.0040	0.0000	0.00
18	4.25	2.1600	0.0090	0.1620	0.0995	0.0007	0.0565	0.0047	0.0000	0.00
19	4.50	2.1600	0.0090	0.1710	0.1050	0.0007	0.0591	0.0054	0.0000	0.00
20	4.75	2.1600	0.0090	0.1800	0.1105	0.0008	0.0617	0.0061	0.0000	0.00
21	5.00	4.1100	0.0171	0.1971	0.1162	0.0009	0.0721	0.0069	0.0000	0.00
22	5.25	4.1100	0.0171	0.2142	0.1219	0.0010	0.0822	0.0079	0.0000	0.00
23	5.50	4.1100	0.0171	0.2314	0.1276	0.0012	0.0921	0.0091	0.0000	0.00
24	5.75	4.1100	0.0171	0.2485	0.1334	0.0013	0.1019	0.0104	0.0000	0.00
25	6.00	4.1100	0.0171	0.2656	0.1391	0.0014	0.1114	0.0120	0.0000	0.01
26	6.25	4.1100	0.0171	0.2827	0.1448	0.0016	0.1207	0.0138	0.0000	0.01
27	6.50	4.1100	0.0171	0.2999	0.1505	0.0017	0.1298	0.0157	0.0000	0.01

Figure 8. (continued).

28	6.75	4.1100	0.0171	0.3170	0.1561	0.0019	0.1387	0.0179	0.0000	0.02
29	7.00	4.1100	0.0171	0.3341	0.1618	0.0021	0.1473	0.0203	0.0000	0.02
30	7.25	4.1100	0.0171	0.3512	0.1675	0.0023	0.1558	0.0229	0.0000	0.03
31	7.50	4.1100	0.0171	0.3684	0.1732	0.0025	0.1640	0.0257	0.0000	0.04
32	7.75	4.1100	0.0171	0.3855	0.1788	0.0027	0.1720	0.0287	0.0000	0.05
33	8.00	4.1100	0.0171	0.4026	0.1845	0.0029	0.1798	0.0320	0.0000	0.06
34	8.25	4.1100	0.0171	0.4197	0.1901	0.0032	0.1873	0.0354	0.0000	0.08
35	8.50	4.1100	0.0171	0.4369	0.1958	0.0035	0.1947	0.0391	0.0000	0.10
36	8.75	4.1100	0.0171	0.4540	0.2014	0.0037	0.2018	0.0430	0.0000	0.12
37	9.00	4.1100	0.0171	0.4711	0.2070	0.0040	0.2088	0.0470	0.0000	0.14
38	9.25	4.1100	0.0171	0.4882	0.2126	0.0043	0.2155	0.0513	0.0000	0.16
39	9.50	4.1100	0.0171	0.5054	0.2183	0.0046	0.2221	0.0557	0.0000	0.19
40	9.75	4.1100	0.0171	0.5225	0.2239	0.0050	0.2284	0.0604	0.0000	0.23
41	10.00	7.4400	0.0310	0.5535	0.2295	0.0053	0.2480	0.0652	0.0000	0.27
42	10.25	7.4400	0.0310	0.5845	0.2351	0.0057	0.2669	0.0707	0.0000	0.32
43	10.50	7.4400	0.0310	0.6155	0.2406	0.0061	0.2851	0.0769	0.0000	0.38
44	10.75	7.4400	0.0310	0.6465	0.2462	0.0065	0.3027	0.0837	0.0000	0.45
45	11.00	7.4400	0.0310	0.6775	0.2518	0.0069	0.3196	0.0911	0.0000	0.54
46	11.25	7.4400	0.0310	0.7085	0.2574	0.0073	0.3358	0.0992	0.0000	0.64
47	11.50	7.4400	0.0310	0.7395	0.2629	0.0078	0.3514	0.1080	0.0000	0.76
48	11.75	7.4400	0.0310	0.7705	0.2685	0.0083	0.3664	0.1173	0.0000	0.90
49	12.00	7.4400	0.0310	0.8015	0.2740	0.0088	0.3808	0.1273	0.0000	1.06
50	12.25	7.4400	0.0310	0.8325	0.2796	0.0093	0.3945	0.1379	0.0000	1.23
51	12.50	7.4400	0.0310	0.8635	0.2851	0.0098	0.4077	0.1491	0.0001	1.44
52	12.75	7.4400	0.0310	0.8945	0.2906	0.0104	0.4203	0.1608	0.0001	1.67
53	13.00	7.4400	0.0310	0.9255	0.2962	0.0110	0.4324	0.1731	0.0001	1.92
54	13.25	7.4400	0.0310	0.9565	0.3017	0.0116	0.4439	0.1859	0.0001	2.21
55	13.50	7.4400	0.0310	0.9875	0.3072	0.0122	0.4549	0.1992	0.0001	2.53
56	13.75	7.4400	0.0310	1.0185	0.3127	0.0129	0.4655	0.2131	0.0001	2.88
57	14.00	7.4400	0.0310	1.0495	0.3182	0.0135	0.4755	0.2274	0.0001	3.27
58	14.25	7.4400	0.0310	1.0805	0.3237	0.0142	0.4851	0.2421	0.0002	3.70
59	14.50	7.4400	0.0310	1.1115	0.3292	0.0150	0.4942	0.2573	0.0002	4.18
60	14.75	7.4400	0.0310	1.1425	0.3346	0.0157	0.5030	0.2730	0.0002	4.70
61	15.00	3.0800	0.0128	1.1553	0.3401	0.0164	0.4941	0.2890	0.0002	5.24
62	15.25	3.0800	0.0128	1.1682	0.3456	0.0172	0.4857	0.3045	0.0003	5.79
63	15.50	3.0800	0.0128	1.1810	0.3510	0.0180	0.4779	0.3194	0.0003	6.37
64	15.75	3.0800	0.0128	1.1938	0.3565	0.0188	0.4704	0.3338	0.0003	6.98
65	16.00	3.0800	0.0128	1.2067	0.3619	0.0196	0.4634	0.3478	0.0004	7.60
66	16.25	3.0800	0.0128	1.2195	0.3674	0.0205	0.4568	0.3613	0.0004	8.25
67	16.50	3.0800	0.0128	1.2323	0.3728	0.0213	0.4505	0.3745	0.0005	8.93
68	16.75	3.0800	0.0128	1.2452	0.3782	0.0222	0.4445	0.3873	0.0005	9.64
69	17.00	3.0800	0.0128	1.2580	0.3837	0.0231	0.4389	0.3997	0.0006	10.37
70	17.25	3.0800	0.0128	1.2708	0.3891	0.0240	0.4335	0.4119	0.0006	11.14
71	17.50	3.0800	0.0128	1.2837	0.3945	0.0248	0.4284	0.4237	0.0007	11.95
72	17.75	3.0800	0.0128	1.2965	0.3999	0.0258	0.4236	0.4352	0.0008	12.79
73	18.00	3.0800	0.0128	1.3093	0.4053	0.0267	0.4190	0.4465	0.0009	13.68
74	18.25	3.0800	0.0128	1.3222	0.4107	0.0276	0.4146	0.4576	0.0009	14.61
75	18.50	3.0800	0.0128	1.3350	0.4161	0.0285	0.4105	0.4684	0.0010	15.59
76	18.75	3.0800	0.0128	1.3478	0.4214	0.0295	0.4065	0.4790	0.0011	16.63
77	19.00	3.0800	0.0128	1.3606	0.4268	0.0304	0.4028	0.4893	0.0012	17.72
78	19.25	3.0800	0.0128	1.3735	0.4322	0.0314	0.3992	0.4995	0.0013	18.87

Figure 8. (continued).

79	19.50	3.0800	0.0128	1.3863	0.4375	0.0323	0.3956	0.5095	0.0014	20.10
80	19.75	3.0800	0.0128	1.3991	0.4429	0.0333	0.3925	0.5193	0.0016	21.40
81	20.00	1.9200	0.0080	1.4071	0.4482	0.0343	0.3848	0.5290	0.0017	22.76
82	20.25	1.9200	0.0080	1.4151	0.4536	0.0353	0.3774	0.5383	0.0018	24.20
83	20.50	1.9200	0.0080	1.4231	0.4589	0.0362	0.3704	0.5472	0.0020	25.72
84	20.75	1.9200	0.0080	1.4311	0.4642	0.0372	0.3636	0.5558	0.0021	27.32
85	21.00	1.9200	0.0080	1.4391	0.4695	0.0382	0.3571	0.5641	0.0023	29.01
86	21.25	1.9200	0.0080	1.4471	0.4749	0.0392	0.3509	0.5721	0.0024	30.81
87	21.50	1.9200	0.0080	1.4551	0.4802	0.0402	0.3450	0.5799	0.0026	32.71
88	21.75	1.9200	0.0080	1.4631	0.4855	0.0412	0.3393	0.5873	0.0028	34.72
89	22.00	1.9200	0.0080	1.4711	0.4908	0.0422	0.3338	0.5946	0.0030	36.85
90	22.25	1.9200	0.0080	1.4791	0.4960	0.0432	0.3285	0.6015	0.0032	39.11
91	22.50	1.9200	0.0080	1.4871	0.5013	0.0443	0.3235	0.6083	0.0035	41.51
92	22.75	1.9200	0.0080	1.4951	0.5066	0.0453	0.3186	0.6149	0.0037	44.05
93	23.00	1.9200	0.0080	1.5031	0.5119	0.0463	0.3139	0.6212	0.0040	46.74
94	23.25	1.9200	0.0080	1.5111	0.5171	0.0473	0.3094	0.6273	0.0042	49.59
95	23.50	1.9200	0.0080	1.5191	0.5224	0.0483	0.3051	0.6333	0.0045	52.61
96	23.75	1.9200	0.0080	1.5271	0.5277	0.0493	0.3009	0.6391	0.0048	55.81
97	24.00	1.9200	0.0080	1.5351	0.5329	0.0503	0.2969	0.6447	0.0052	59.19
98	24.25	1.9200	0.0080	1.5431	0.5381	0.0514	0.2930	0.6501	0.0055	62.76
99	24.50	1.9200	0.0080	1.5511	0.5434	0.0524	0.2893	0.6554	0.0059	66.54
100	24.75	1.9200	0.0080	1.5591	0.5486	0.0534	0.2857	0.6606	0.0063	70.53
101	25.00	1.5600	0.0065	1.5656	0.5538	0.0544	0.2807	0.6656	0.0067	74.75
102	25.25	1.5600	0.0065	1.5721	0.5590	0.0554	0.2760	0.6704	0.0071	79.20
103	25.50	1.5600	0.0065	1.5786	0.5643	0.0565	0.2714	0.6750	0.0076	83.92
104	25.75	1.5600	0.0065	1.5851	0.5695	0.0575	0.2670	0.6794	0.0081	88.92
105	26.00	1.5600	0.0065	1.5916	0.5747	0.0585	0.2627	0.6836	0.0086	94.25
106	26.25	1.5600	0.0065	1.5981	0.5799	0.0595	0.2585	0.6877	0.0092	99.95
107	26.50	1.5600	0.0065	1.6046	0.5850	0.0605	0.2545	0.6916	0.0097	106.08
108	26.75	1.5600	0.0065	1.6111	0.5902	0.0616	0.2506	0.6954	0.0104	112.72
109	27.00	1.5600	0.0065	1.6176	0.5954	0.0626	0.2469	0.6990	0.0110	120.01
110	27.25	1.5600	0.0065	1.6241	0.6006	0.0636	0.2432	0.7024	0.0117	128.08
111	27.50	1.5600	0.0065	1.6306	0.6057	0.0646	0.2397	0.7057	0.0125	137.12
112	27.75	1.5600	0.0065	1.6371	0.6109	0.0656	0.2363	0.7089	0.0133	147.38
113	28.00	1.5600	0.0065	1.6436	0.6160	0.0666	0.2330	0.7119	0.0142	159.15
114	28.25	1.5600	0.0065	1.6501	0.6212	0.0676	0.2297	0.7147	0.0152	172.78
115	28.50	1.5600	0.0065	1.6566	0.6263	0.0686	0.2266	0.7174	0.0162	188.68
116	28.75	1.5600	0.0065	1.6631	0.6314	0.0697	0.2236	0.7199	0.0174	207.30
117	29.00	1.5600	0.0065	1.6696	0.6366	0.0707	0.2206	0.7222	0.0186	229.12
118	29.25	1.5600	0.0065	1.6761	0.6417	0.0717	0.2178	0.7244	0.0200	254.62
119	29.50	1.5600	0.0065	1.6826	0.6468	0.0727	0.2150	0.7264	0.0216	284.23
120	29.75	1.5600	0.0065	1.6891	0.6519	0.0737	0.2123	0.7281	0.0234	318.31
121	30.00	1.3200	0.0055	1.6946	0.6570	0.0747	0.2087	0.7296	0.0253	357.06
122	30.25	1.3200	0.0055	1.7001	0.6621	0.0757	0.2052	0.7309	0.0276	400.54
123	30.50	1.3200	0.0055	1.7056	0.6672	0.0767	0.2018	0.7318	0.0300	448.57
124	30.75	1.3200	0.0055	1.7111	0.6723	0.0776	0.1985	0.7324	0.0328	500.75
125	31.00	1.3200	0.0055	1.7166	0.6774	0.0786	0.1953	0.7326	0.0359	556.46
126	31.25	1.3200	0.0055	1.7221	0.6824	0.0796	0.1922	0.7325	0.0393	614.89
127	31.50	1.3200	0.0055	1.7276	0.6875	0.0806	0.1891	0.7320	0.0430	675.06
128	31.75	1.3200	0.0055	1.7331	0.6926	0.0816	0.1862	0.7311	0.0471	735.95

Figure 8. (continued).

129	32.00	1.3200	0.0055	1.7386	0.6976	0.0826	0.1833	0.7298	0.0515	796.50
130	32.25	1.3200	0.0055	1.7441	0.7027	0.0835	0.1805	0.7281	0.0563	855.68
131	32.50	1.3200	0.0055	1.7496	0.7077	0.0845	0.1777	0.7259	0.0613	912.58
132	32.75	1.3200	0.0055	1.7551	0.7128	0.0855	0.1750	0.7234	0.0667	966.42
133	33.00	1.3200	0.0055	1.7606	0.7178	0.0864	0.1724	0.7206	0.0723	1016.57
134	33.25	1.3200	0.0055	1.7661	0.7228	0.0874	0.1698	0.7174	0.0782	1062.59
135	33.50	1.3200	0.0055	1.7716	0.7278	0.0883	0.1673	0.7138	0.0843	1104.17
136	33.75	1.3200	0.0055	1.7771	0.7328	0.0893	0.1649	0.7099	0.0906	1141.17
137	34.00	1.3200	0.0055	1.7826	0.7379	0.0902	0.1625	0.7058	0.0971	1173.57
138	34.25	1.3200	0.0055	1.7881	0.7429	0.0912	0.1602	0.7014	0.1038	1201.44
139	34.50	1.3200	0.0055	1.7936	0.7478	0.0921	0.1579	0.6968	0.1106	1224.96
140	34.75	1.3200	0.0055	1.7991	0.7528	0.0930	0.1556	0.6920	0.1175	1244.35
141	35.00	1.2000	0.0050	1.8041	0.7578	0.0940	0.1530	0.6870	0.1244	1259.87
142	35.25	1.2000	0.0050	1.8091	0.7628	0.0949	0.1503	0.6819	0.1315	1271.82
143	35.50	1.2000	0.0050	1.8141	0.7678	0.0958	0.1478	0.6766	0.1386	1280.48
144	35.75	1.2000	0.0050	1.8191	0.7727	0.0967	0.1453	0.6713	0.1457	1286.17
145	36.00	1.2000	0.0050	1.8241	0.7777	0.0976	0.1428	0.6658	0.1528	1289.18
146	36.25	1.2000	0.0050	1.8291	0.7826	0.0985	0.1405	0.6603	0.1600	1289.78
147	36.50	1.2000	0.0050	1.8341	0.7874	0.0994	0.1382	0.6547	0.1671	1288.25
148	36.75	1.2000	0.0050	1.8391	0.7922	0.1003	0.1361	0.6491	0.1742	1284.82
149	37.00	1.2000	0.0050	1.8441	0.7970	0.1012	0.1339	0.6434	0.1813	1279.73
150	37.25	1.2000	0.0050	1.8491	0.8017	0.1021	0.1319	0.6377	0.1884	1273.18
151	37.50	1.2000	0.0050	1.8541	0.8064	0.1030	0.1299	0.6321	0.1954	1265.36
152	37.75	1.2000	0.0050	1.8591	0.8111	0.1039	0.1280	0.6264	0.2023	1256.44
153	38.00	1.2000	0.0050	1.8641	0.8157	0.1048	0.1261	0.6208	0.2092	1246.57
154	38.25	1.2000	0.0050	1.8691	0.8203	0.1057	0.1244	0.6151	0.2161	1235.89
155	38.50	1.2000	0.0050	1.8741	0.8246	0.1065	0.1229	0.6096	0.2229	1224.51
156	38.75	1.2000	0.0050	1.8791	0.8289	0.1074	0.1215	0.6040	0.2296	1212.56
157	39.00	1.2000	0.0050	1.8841	0.8331	0.1083	0.1201	0.5985	0.2362	1200.11
158	39.25	1.2000	0.0050	1.8891	0.8373	0.1091	0.1189	0.5930	0.2428	1187.26
159	39.50	1.2000	0.0050	1.8941	0.8414	0.1100	0.1177	0.5876	0.2493	1174.08
160	39.75	1.2000	0.0050	1.8991	0.8454	0.1108	0.1166	0.5822	0.2557	1160.64
161	40.00	1.2000	0.0050	1.9041	0.8494	0.1117	0.1156	0.5769	0.2621	1146.99
162	40.25	1.2000	0.0050	1.9091	0.8534	0.1125	0.1147	0.5717	0.2684	1133.18
163	40.50	1.2000	0.0050	1.9141	0.8573	0.1134	0.1138	0.5665	0.2746	1119.27
164	40.75	1.2000	0.0050	1.9191	0.8612	0.1142	0.1129	0.5614	0.2807	1105.29
165	41.00	1.2000	0.0050	1.9241	0.8650	0.1150	0.1121	0.5563	0.2867	1091.26
166	41.25	1.2000	0.0050	1.9291	0.8689	0.1159	0.1112	0.5513	0.2927	1077.24
167	41.50	1.2000	0.0050	1.9341	0.8728	0.1167	0.1105	0.5463	0.2986	1063.23
168	41.75	1.2000	0.0050	1.9391	0.8767	0.1175	0.1097	0.5415	0.3044	1049.27
169	42.00	1.2000	0.0050	1.9441	0.8805	0.1183	0.1090	0.5367	0.3101	1035.37
170	42.25	1.2000	0.0050	1.9491	0.8843	0.1191	0.1082	0.5319	0.3158	1021.55
171	42.50	1.2000	0.0050	1.9541	0.8882	0.1200	0.1076	0.5272	0.3214	1007.82
172	42.75	1.2000	0.0050	1.9591	0.8920	0.1208	0.1069	0.5226	0.3269	994.21
173	43.00	1.2000	0.0050	1.9641	0.8958	0.1216	0.1062	0.5181	0.3323	980.71
174	43.25	1.2000	0.0050	1.9691	0.8996	0.1224	0.1056	0.5136	0.3377	967.35
175	43.50	1.2000	0.0050	1.9741	0.9034	0.1232	0.1050	0.5092	0.3430	954.12
176	43.75	1.2000	0.0050	1.9791	0.9072	0.1240	0.1044	0.5048	0.3482	941.04
177	44.00	1.2000	0.0050	1.9841	0.9110	0.1248	0.1039	0.5006	0.3533	928.11
178	44.25	1.2000	0.0050	1.9891	0.9147	0.1256	0.1033	0.4963	0.3584	915.33

Figure 8. (continued).

179	44.50	1.2000	0.0050	1.9941	0.9185	0.1263	0.1028	0.4922	0.3634	902.72
180	44.75	1.2000	0.0050	1.9991	0.9223	0.1271	0.1023	0.4881	0.3683	890.27
181	45.00	0.6000	0.0025	2.0016	0.9252	0.1279	0.1001	0.4841	0.3732	877.99
182	45.25	0.6000	0.0025	2.0041	0.9282	0.1287	0.0980	0.4800	0.3780	865.84
183	45.50	0.6000	0.0025	2.0066	0.9312	0.1295	0.0959	0.4760	0.3827	853.87
184	45.75	0.6000	0.0025	2.0091	0.9341	0.1302	0.0939	0.4721	0.3874	842.07
185	46.00	0.6000	0.0025	2.0116	0.9371	0.1310	0.0919	0.4681	0.3920	830.43
186	46.25	0.6000	0.0025	2.0141	0.9401	0.1318	0.0900	0.4642	0.3965	818.96
187	46.50	0.6000	0.0025	2.0166	0.9430	0.1325	0.0882	0.4603	0.4010	807.66
188	46.75	0.6000	0.0025	2.0191	0.9459	0.1333	0.0864	0.4564	0.4054	796.52
189	47.00	0.6000	0.0025	2.0216	0.9488	0.1341	0.0846	0.4526	0.4097	785.55
190	47.25	0.6000	0.0025	2.0241	0.9517	0.1348	0.0829	0.4487	0.4140	774.75
191	47.50	0.6000	0.0025	2.0266	0.9546	0.1356	0.0812	0.4449	0.4182	764.12
192	47.75	0.6000	0.0025	2.0291	0.9575	0.1363	0.0796	0.4412	0.4224	753.65
193	48.00	0.6000	0.0025	2.0316	0.9604	0.1371	0.0780	0.4374	0.4265	743.33
194	48.25	0.6000	0.0025	2.0341	0.9633	0.1378	0.0764	0.4337	0.4306	733.19
195	48.50	0.6000	0.0025	2.0366	0.9662	0.1385	0.0749	0.4300	0.4346	723.20
196	48.75	0.6000	0.0025	2.0391	0.9691	0.1393	0.0734	0.4264	0.4386	713.37
197	49.00	0.6000	0.0025	2.0416	0.9720	0.1400	0.0719	0.4227	0.4425	703.68
198	49.25	0.6000	0.0025	2.0441	0.9749	0.1407	0.0704	0.4191	0.4463	694.16
199	49.50	0.6000	0.0025	2.0466	0.9778	0.1415	0.0690	0.4156	0.4501	684.79
200	49.75	0.6000	0.0025	2.0491	0.9807	0.1422	0.0676	0.4120	0.4538	675.56
201	50.00	0.6000	0.0025	2.0516	0.9836	0.1429	0.0662	0.4085	0.4575	666.49
202	50.25	0.6000	0.0025	2.0541	0.9865	0.1436	0.0649	0.4051	0.4612	657.56
203	50.50	0.6000	0.0025	2.0566	0.9893	0.1443	0.0636	0.4016	0.4648	648.77
204	50.75	0.6000	0.0025	2.0591	0.9922	0.1450	0.0623	0.3982	0.4683	640.12
205	51.00	0.6000	0.0025	2.0616	0.9950	0.1457	0.0610	0.3948	0.4718	631.62
206	51.25	0.6000	0.0025	2.0641	0.9979	0.1464	0.0598	0.3915	0.4753	623.25
207	51.50	0.6000	0.0025	2.0666	1.0007	0.1471	0.0586	0.3882	0.4787	615.01
208	51.75	0.6000	0.0025	2.0691	1.0035	0.1478	0.0574	0.3849	0.4820	606.91
209	52.00	0.6000	0.0025	2.0716	1.0063	0.1485	0.0563	0.3817	0.4853	598.94
210	52.25	0.6000	0.0025	2.0741	1.0090	0.1492	0.0552	0.3785	0.4886	591.09
211	52.50	0.6000	0.0025	2.0766	1.0118	0.1499	0.0542	0.3753	0.4918	583.37
212	52.75	0.6000	0.0025	2.0791	1.0146	0.1506	0.0531	0.3721	0.4950	575.78
213	53.00	0.6000	0.0025	2.0816	1.0173	0.1513	0.0521	0.3690	0.4982	568.31
214	53.25	0.6000	0.0025	2.0841	1.0200	0.1520	0.0511	0.3659	0.5013	560.96
215	53.50	0.6000	0.0025	2.0866	1.0227	0.1526	0.0501	0.3629	0.5044	553.73
216	53.75	0.6000	0.0025	2.0891	1.0254	0.1533	0.0492	0.3598	0.5074	546.62
217	54.00	0.6000	0.0025	2.0916	1.0280	0.1540	0.0483	0.3568	0.5104	539.61
218	54.25	0.6000	0.0025	2.0941	1.0306	0.1546	0.0476	0.3539	0.5133	532.72
219	54.50	0.6000	0.0025	2.0966	1.0331	0.1553	0.0468	0.3510	0.5162	525.95
220	54.75	0.6000	0.0025	2.0991	1.0356	0.1560	0.0461	0.3481	0.5191	519.28
221	55.00	0.6000	0.0025	2.1016	1.0380	0.1566	0.0455	0.3452	0.5219	512.72
222	55.25	0.6000	0.0025	2.1041	1.0403	0.1573	0.0450	0.3424	0.5248	506.27
223	55.50	0.6000	0.0025	2.1066	1.0426	0.1579	0.0445	0.3396	0.5275	499.91
224	55.75	0.6000	0.0025	2.1091	1.0449	0.1586	0.0441	0.3368	0.5303	493.65
225	56.00	0.6000	0.0025	2.1116	1.0471	0.1592	0.0437	0.3341	0.5330	487.50
226	56.25	0.6000	0.0025	2.1141	1.0493	0.1599	0.0433	0.3313	0.5356	481.45
227	56.50	0.6000	0.0025	2.1166	1.0515	0.1605	0.0430	0.3287	0.5383	475.49
228	56.75	0.6000	0.0025	2.1191	1.0537	0.1611	0.0426	0.3260	0.5409	469.62

Figure 8. (continued).

229	57.00	0.6000	0.0025	2.1216	1.0558	0.1618	0.0423	0.3234	0.5434	463.85
230	57.25	0.6000	0.0025	2.1241	1.0580	0.1624	0.0420	0.3208	0.5460	456.17
231	57.50	0.6000	0.0025	2.1266	1.0602	0.1630	0.0417	0.3182	0.5485	452.57
232	57.75	0.6000	0.0025	2.1291	1.0624	0.1637	0.0414	0.3157	0.5509	447.06
233	58.00	0.6000	0.0025	2.1316	1.0645	0.1643	0.0411	0.3132	0.5534	441.64
234	58.25	0.6000	0.0025	2.1341	1.0667	0.1649	0.0408	0.3107	0.5558	436.30
235	58.50	0.6000	0.0025	2.1366	1.0688	0.1655	0.0406	0.3083	0.5582	431.04
236	58.75	0.6000	0.0025	2.1391	1.0710	0.1661	0.0403	0.3058	0.5606	425.86
237	59.00	0.6000	0.0025	2.1416	1.0731	0.1668	0.0401	0.3034	0.5629	420.77
238	59.25	0.6000	0.0025	2.1441	1.0752	0.1674	0.0399	0.3011	0.5652	415.74
239	59.50	0.6000	0.0025	2.1466	1.0773	0.1680	0.0397	0.2987	0.5675	410.80
240	59.75	0.6000	0.0025	2.1491	1.0794	0.1686	0.0395	0.2964	0.5697	405.93
241	60.00	0.0	0.0	2.1491	1.0799	0.1692	0.0384	0.2941	0.5719	401.12
242	60.25	0.0	0.0	2.1491	1.0804	0.1698	0.0374	0.2918	0.5741	396.40
243	60.50	0.0	0.0	2.1491	1.0810	0.1704	0.0363	0.2895	0.5763	391.74
244	60.75	0.0	0.0	2.1491	1.0815	0.1710	0.0353	0.2873	0.5784	387.15
245	61.00	0.0	0.0	2.1491	1.0820	0.1716	0.0344	0.2850	0.5806	382.63
246	61.25	0.0	0.0	2.1491	1.0825	0.1722	0.0334	0.2827	0.5827	378.18
247	61.50	0.0	0.0	2.1491	1.0830	0.1728	0.0325	0.2804	0.5847	373.79
248	61.75	0.0	0.0	2.1491	1.0835	0.1734	0.0316	0.2782	0.5868	369.46
249	62.00	0.0	0.0	2.1491	1.0840	0.1739	0.0307	0.2759	0.5888	365.20
250	62.25	0.0	0.0	2.1491	1.0845	0.1745	0.0298	0.2737	0.5908	361.00
251	62.50	0.0	0.0	2.1491	1.0850	0.1751	0.0290	0.2715	0.5928	356.86
252	62.75	0.0	0.0	2.1491	1.0854	0.1757	0.0282	0.2692	0.5947	352.77
253	63.00	0.0	0.0	2.1491	1.0859	0.1762	0.0274	0.2670	0.5967	348.75
254	63.25	0.0	0.0	2.1491	1.0864	0.1768	0.0266	0.2648	0.5986	344.78
255	63.50	0.0	0.0	2.1491	1.0868	0.1774	0.0259	0.2626	0.6004	340.87
256	63.75	0.0	0.0	2.1491	1.0873	0.1779	0.0251	0.2604	0.6023	337.01
257	64.00	0.0	0.0	2.1491	1.0878	0.1785	0.0244	0.2582	0.6042	333.20
258	64.25	0.0	0.0	2.1491	1.0882	0.1791	0.0237	0.2561	0.6060	329.45
259	64.50	0.0	0.0	2.1491	1.0887	0.1796	0.0230	0.2539	0.6078	325.75
260	64.75	0.0	0.0	2.1491	1.0892	0.1802	0.0223	0.2518	0.6096	322.10
261	65.00	0.0	0.0	2.1491	1.0896	0.1807	0.0216	0.2497	0.6113	318.50
262	65.25	0.0	0.0	2.1491	1.0901	0.1813	0.0209	0.2475	0.6131	314.95
263	65.50	0.0	0.0	2.1491	1.0906	0.1818	0.0203	0.2454	0.6148	311.44
264	65.75	0.0	0.0	2.1491	1.0910	0.1823	0.0196	0.2433	0.6165	307.98
265	66.00	0.0	0.0	2.1491	1.0915	0.1829	0.0190	0.2413	0.6182	304.57
266	66.25	0.0	0.0	2.1491	1.0920	0.1834	0.0184	0.2392	0.6199	301.20
267	66.50	0.0	0.0	2.1491	1.0924	0.1840	0.0177	0.2371	0.6215	297.88
268	66.75	0.0	0.0	2.1491	1.0929	0.1845	0.0171	0.2351	0.6231	294.60
269	67.00	0.0	0.0	2.1491	1.0933	0.1850	0.0165	0.2330	0.6248	291.35
270	67.25	0.0	0.0	2.1491	1.0938	0.1855	0.0159	0.2310	0.6264	288.16
271	67.50	0.0	0.0	2.1491	1.0943	0.1861	0.0154	0.2290	0.6279	285.00
272	67.75	0.0	0.0	2.1491	1.0947	0.1866	0.0148	0.2270	0.6295	281.89
273	68.00	0.0	0.0	2.1491	1.0951	0.1871	0.0143	0.2250	0.6310	278.82
274	68.25	0.0	0.0	2.1491	1.0956	0.1876	0.0137	0.2231	0.6326	275.78
275	68.50	0.0	0.0	2.1491	1.0960	0.1881	0.0132	0.2211	0.6341	272.78
276	68.75	0.0	0.0	2.1491	1.0964	0.1886	0.0127	0.2192	0.6356	267.82
277	69.00	0.0	0.0	2.1491	1.0968	0.1891	0.0122	0.2173	0.6371	266.89
278	69.25	0.0	0.0	2.1491	1.0973	0.1896	0.0117	0.2153	0.6385	264.01

Figure 8. (continued).

279	69.50	0.0	0.0	2.1491	1.0977	0.1901	0.0112	0.2134	0.6400	261.15
280	69.75	0.0	0.0	2.1491	1.0981	0.1906	0.0107	0.2116	0.6414	258.34
281	70.00	0.0	0.0	2.1491	1.0985	0.1911	0.0102	0.2097	0.6428	255.55
282	70.25	0.0	0.0	2.1491	1.0989	0.1916	0.0098	0.2078	0.6442	252.80
283	70.50	0.0	0.0	2.1491	1.0993	0.1921	0.0093	0.2060	0.6456	250.09
284	70.75	0.0	0.0	2.1491	1.0997	0.1926	0.0089	0.2042	0.6470	247.40
285	71.00	0.0	0.0	2.1491	1.1001	0.1930	0.0084	0.2023	0.6483	244.75
286	71.25	0.0	0.0	2.1491	1.1005	0.1935	0.0080	0.2005	0.6497	242.13
287	71.50	0.0	0.0	2.1491	1.1008	0.1940	0.0076	0.1987	0.6510	239.54
288	71.75	0.0	0.0	2.1491	1.1012	0.1945	0.0072	0.1970	0.6523	236.98
289	72.00	0.0	0.0	2.1491	1.1015	0.1949	0.0068	0.1952	0.6536	234.45
290	72.25	0.0	0.0	2.1491	1.1019	0.1954	0.0065	0.1935	0.6549	231.95
291	72.50	0.0	0.0	2.1491	1.1022	0.1959	0.0061	0.1917	0.6562	229.48
292	72.75	0.0	0.0	2.1491	1.1025	0.1963	0.0058	0.1900	0.6574	227.03
293	73.00	0.0	0.0	2.1491	1.1028	0.1968	0.0054	0.1883	0.6587	224.62
294	73.25	0.0	0.0	2.1491	1.1031	0.1972	0.0051	0.1866	0.6599	222.23
295	73.50	0.0	0.0	2.1491	1.1034	0.1977	0.0048	0.1849	0.6611	219.87
296	73.75	0.0	0.0	2.1491	1.1037	0.1981	0.0044	0.1833	0.6623	217.53
297	74.00	0.0	0.0	2.1491	1.1040	0.1986	0.0042	0.1816	0.6635	215.23
298	74.25	0.0	0.0	2.1491	1.1043	0.1990	0.0039	0.1800	0.6647	212.95
299	74.50	0.0	0.0	2.1491	1.1045	0.1995	0.0036	0.1784	0.6658	210.69
300	74.75	0.0	0.0	2.1491	1.1048	0.1999	0.0033	0.1768	0.6670	208.46
301	75.00	0.0	0.0	2.1491	1.1051	0.2003	0.0030	0.1752	0.6681	206.25
302	75.25	0.0	0.0	2.1491	1.1053	0.2008	0.0028	0.1736	0.6693	204.07
303	75.50	0.0	0.0	2.1491	1.1055	0.2012	0.0025	0.1720	0.6704	201.92
304	75.75	0.0	0.0	2.1491	1.1058	0.2016	0.0023	0.1705	0.6715	199.78
305	76.00	0.0	0.0	2.1491	1.1060	0.2021	0.0021	0.1689	0.6726	197.68
306	76.25	0.0	0.0	2.1491	1.1062	0.2025	0.0019	0.1674	0.6737	195.59
307	76.50	0.0	0.0	2.1491	1.1063	0.2029	0.0017	0.1659	0.6747	193.52
308	76.75	0.0	0.0	2.1491	1.1065	0.2033	0.0016	0.1644	0.6758	191.48
309	77.00	0.0	0.0	2.1491	1.1066	0.2037	0.0014	0.1629	0.6769	189.46
310	77.25	0.0	0.0	2.1491	1.1068	0.2041	0.0013	0.1615	0.6779	187.47
311	77.50	0.0	0.0	2.1491	1.1069	0.2046	0.0011	0.1600	0.6789	185.49
312	77.75	0.0	0.0	2.1491	1.1070	0.2050	0.0010	0.1586	0.6799	183.54
313	78.00	0.0	0.0	2.1491	1.1071	0.2054	0.0009	0.1571	0.6809	181.60
314	78.25	0.0	0.0	2.1491	1.1072	0.2058	0.0008	0.1557	0.6819	179.69
315	78.50	0.0	0.0	2.1491	1.1073	0.2062	0.0007	0.1543	0.6829	177.80
316	78.75	0.0	0.0	2.1491	1.1074	0.2066	0.0007	0.1529	0.6839	175.93
317	79.00	0.0	0.0	2.1491	1.1074	0.2070	0.0006	0.1515	0.6849	174.07
318	79.25	0.0	0.0	2.1491	1.1075	0.2074	0.0005	0.1502	0.6858	172.24
319	79.50	0.0	0.0	2.1491	1.1076	0.2077	0.0004	0.1488	0.6868	170.43
320	79.75	0.0	0.0	2.1491	1.1076	0.2081	0.0004	0.1475	0.6877	168.63
321	80.00	0.0	0.0	2.1491	1.1077	0.2085	0.0003	0.1461	0.6886	166.86
322	80.25	0.0	0.0	2.1491	1.1078	0.2089	0.0003	0.1448	0.6895	165.10
323	80.50	0.0	0.0	2.1491	1.1078	0.2093	0.0002	0.1435	0.6904	163.36
324	80.75	0.0	0.0	2.1491	1.1078	0.2097	0.0002	0.1422	0.6913	161.65
325	81.00	0.0	0.0	2.1491	1.1079	0.2100	0.0001	0.1409	0.6922	159.94
326	81.25	0.0	0.0	2.1491	1.1079	0.2104	0.0001	0.1396	0.6931	158.26
327	81.50	0.0	0.0	2.1491	1.1079	0.2108	0.0001	0.1384	0.6940	156.60
328	81.75	0.0	0.0	2.1491	1.1079	0.2112	0.0001	0.1371	0.6948	154.95

Figure 8. (continued).

329	82.00	0.0	0.0	2.1491	1.1080	0.2115	0.0000	0.1359	0.6957	153.32
330	82.25	0.0	0.0	2.1491	1.1080	0.2119	0.0000	0.1347	0.6965	151.70
331	82.50	0.0	0.0	2.1491	1.1080	0.2122	0.0000	0.1335	0.6973	150.10
332	82.75	0.0	0.0	2.1491	1.1080	0.2126	0.0000	0.1323	0.6982	148.53
333	83.00	0.0	0.0	2.1491	1.1080	0.2130	0.0000	0.1311	0.6990	146.96
334	83.25	0.0	0.0	2.1491	1.1080	0.2133	0.0	0.1299	0.6998	145.41
335	83.50	0.0	0.0	2.1491	1.1080	0.2137	0.0	0.1287	0.7006	143.88
336	83.75	0.0	0.0	2.1491	1.1080	0.2140	0.0	0.1276	0.7014	142.37
337	84.00	0.0	0.0	2.1491	1.1080	0.2144	0.0	0.1264	0.7021	140.87
338	84.25	0.0	0.0	2.1491	1.1080	0.2147	0.0	0.1253	0.7029	139.38
339	84.50	0.0	0.0	2.1491	1.1080	0.2151	0.0	0.1241	0.7037	137.91
340	84.75	0.0	0.0	2.1491	1.1080	0.2154	0.0	0.1230	0.7044	136.46
341	85.00	0.0	0.0	2.1491	1.1080	0.2157	0.0	0.1219	0.7052	135.02
342	85.25	0.0	0.0	2.1491	1.1080	0.2161	0.0	0.1208	0.7059	133.59
343	85.50	0.0	0.0	2.1491	1.1080	0.2164	0.0	0.1197	0.7067	132.19
344	85.75	0.0	0.0	2.1491	1.1080	0.2168	0.0	0.1187	0.7074	130.79
345	86.00	0.0	0.0	2.1491	1.1080	0.2171	0.0	0.1176	0.7081	129.41
346	86.25	0.0	0.0	2.1491	1.1080	0.2174	0.0	0.1165	0.7088	128.04
347	86.50	0.0	0.0	2.1491	1.1080	0.2177	0.0	0.1155	0.7095	126.69
348	86.75	0.0	0.0	2.1491	1.1080	0.2181	0.0	0.1145	0.7102	125.36
349	87.00	0.0	0.0	2.1491	1.1080	0.2184	0.0	0.1134	0.7109	124.03
350	87.25	0.0	0.0	2.1491	1.1080	0.2187	0.0	0.1124	0.7116	122.72
351	87.50	0.0	0.0	2.1491	1.1080	0.2190	0.0	0.1114	0.7122	121.42
352	87.75	0.0	0.0	2.1491	1.1080	0.2194	0.0	0.1104	0.7129	120.14
353	88.00	0.0	0.0	2.1491	1.1080	0.2197	0.0	0.1094	0.7136	118.87
354	88.25	0.0	0.0	2.1491	1.1080	0.2200	0.0	0.1084	0.7142	117.61
355	88.50	0.0	0.0	2.1491	1.1080	0.2203	0.0	0.1075	0.7149	116.37
356	88.75	0.0	0.0	2.1491	1.1080	0.2206	0.0	0.1065	0.7155	115.14
357	89.00	0.0	0.0	2.1491	1.1080	0.2209	0.0	0.1055	0.7161	113.92
358	89.25	0.0	0.0	2.1491	1.1080	0.2212	0.0	0.1046	0.7168	112.71
359	89.50	0.0	0.0	2.1491	1.1080	0.2215	0.0	0.1037	0.7174	111.52
360	89.75	0.0	0.0	2.1491	1.1080	0.2218	0.0	0.1027	0.7180	110.34
361	90.00	0.0	0.0	2.1491	1.1080	0.2221	0.0	0.1018	0.7186	109.17

Figure 8. (continued).

the downstream direction. Thus the channel infiltration rate was modified.

Overall disposition of the rainfall 90 minutes after precipitation initiated and 30 minutes after cessation is approximately 52 percent surface infiltrated, 10 percent channel infiltrated, no standing surface water, 5 percent still retained in the channel, and 33 percent having discharged from the basin.

The outflow hydrograph and hyetograph are shown in Figure 9.

Discussion

The peak flow is seen to occur at approximately 35 minutes, a time of concentration approximately estimated by standard equations of engineering hydrology.

The instantaneous peak of approximately 1300 cfs cannot be verified directly. The 100-year synthetic storm has not been recorded at this watershed and there is no station for outflow gaging. Were there a recording gage, it is not likely that it would record discharge at less than a 5 or 10 minute interval. In the hydrograph generated, flow exceeds 1000 cfs for only approximately 10 minutes. Thus recorded data could underestimate the extent of sharp peaks. An additional problem in gaging flood flows in arroyos is bottom scour. Altered bed material often indicates substantial degradation during flooding and subsequent redeposition (Foley, 1978). Estimates based on stage rating curves are

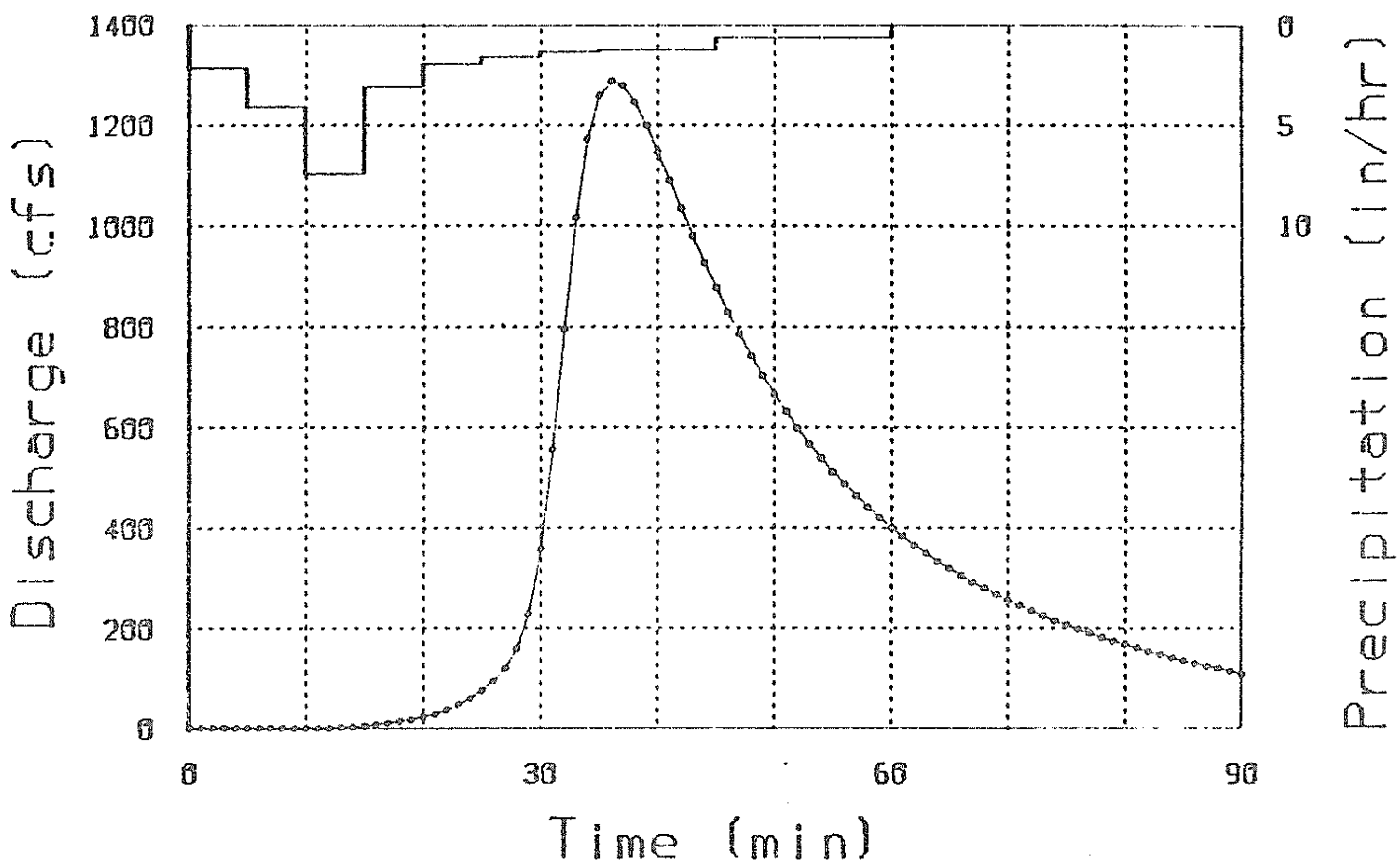

Figure 9. Hydrograph, Four Hills.

prone to be low. All in all, it can be anticipated that field measurements, when available, are subject to significant errors, more likely biasing the estimate negatively.

As the Four Hills Arroyo discharges into a developing urban area, the City of Albuquerque has had interest in proper storm water conveyance. Over several years, approximately six engineering studies have considered runoff in this arroyo. Estimates for the 100-year event ranged from 600 to 1400 cfs (Heggen, 1979; Thomson and Borland, 1979). In that watershed, delineation and rainfall depth was not consistent among the studies, some error may explained. But the large portion of the differences must be attributed to methodology. The rational method, Cook's method, the Colorado urban hydrograph procedure, the Snyder synthetic hydrograph method, the SCS curve number approach, local master-planning formulae and USGS flood frequency regression analysis each contain assumptions that may not be satisfied. Each makes use of constants that may vary for a case of nonhomogeneity.

The hydrograph generated by the model appears to fit reasonably in the range of other estimates. This is not to claim it provides the best estimate, as that cannot be known until the 100-year storm occurs. The model does provide a more rational computational basis for the estimate than do the others. The model can be improved or appropriately tuned for a specific case more justifiably than can the others. The model appears to satisfy its objective.

VERIFICATION ANALYSIS

Watershed

The watershed chosen for verification analysis is a tributary basin to the North Camino Arroyo in northeast Albuquerque, New Mexico, south of Tramway Boulevard and east of Barstow Boulevard. The terrain is alluvial outwash from the Sandia Mountains, typically sloping approximately 3-1/2 percent to the west toward the Rio Grande (Figure 10). The area has long been platted and there are numerous dirt roads but there are no structures. The appearance is of rangeland on low, rolling hills.

The watershed is slightly more than two miles long and narrow, ranging in width from roughly 200 to 900 ft. The drainage area is approximately 150 acres.

Four factors make this site useful for model development; the first factor is data availability. The soil has been classified by the U.S. Soil Conservation Service. Rainfall and runoff data are monitored at the outlet by the U.S. Geological Survey. The City of Albuquerque has 1:24000 phototopographic maps of the area.

The second factor is the watershed's small size. Not only does this make the rainfall data more reliable, but it also allows for smaller quadrants with more accurate average slopes. On the other hand, the smallness means that total flow is low and that "small" changes in the output resulting from small differences in the input (e.g., roughness coefficients) may be significant.

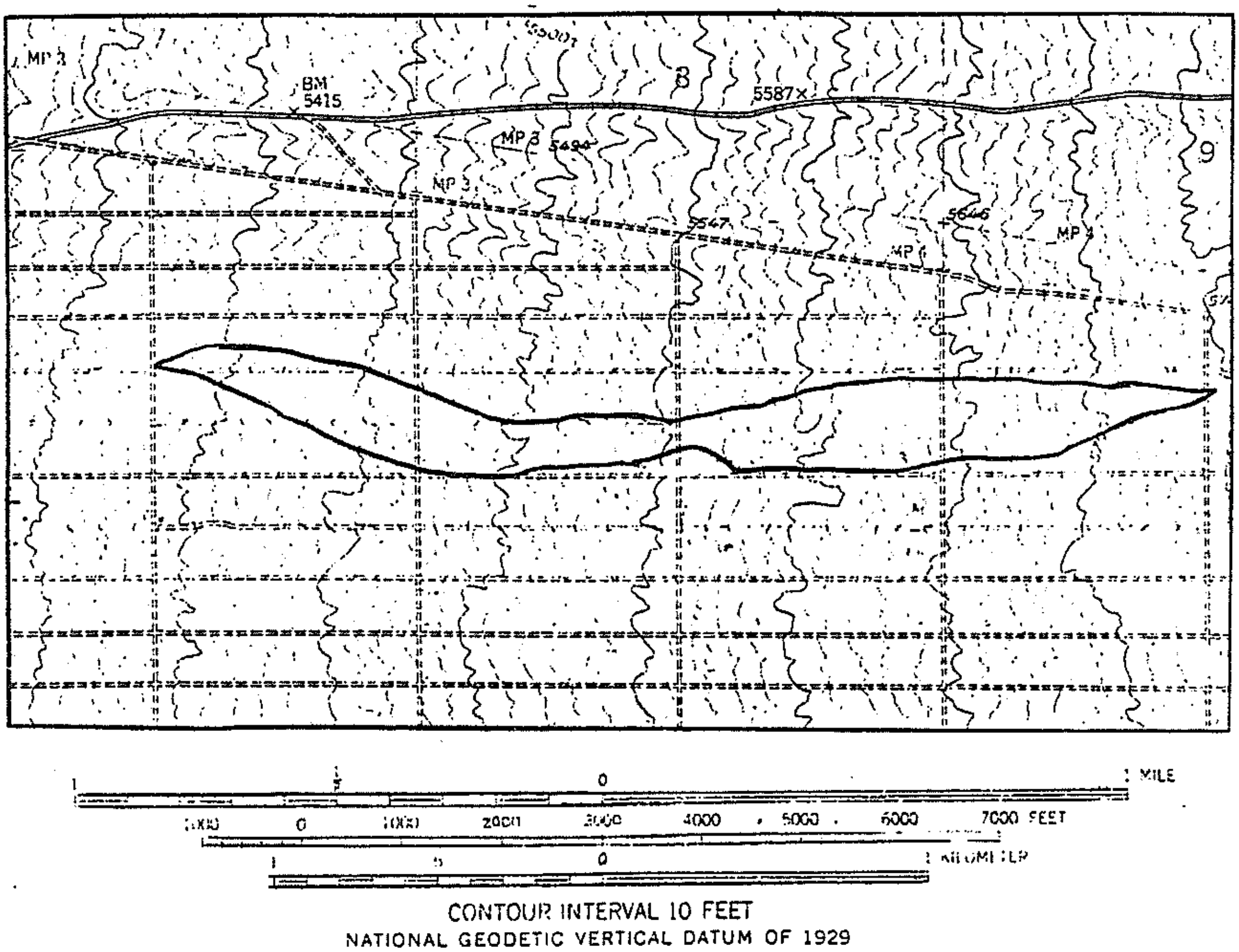

Figure 10. Topography, North Camino tributary.

Third, the long, narrow shape is atypical, though not uncommon in the region, and challenges the stream order/channel width relations embedded in the model. Last is the fact that the main channel is an arroyo not well modeled by standard engineering practice. The channel is normally dry with measurable flow only for short periods after intense storms. The channel is braided in many places; the flow path and width change during a flow even. Manning's n is not constant, but a function of suspended sediment, depth of flow, and brush and weeds in the channel.

Channels

The main channel is head cutting and starts abruptly at approximately 3 ft of width. At the gaging station 11000 ft downstream, it is 19 ft wide, but not by even progression; width frequently varies 50 percent within 200 ft. Braiding and widening at bends account for only part of the variation. By traditional classification, it is a second or third order stream at the gage despite the width.

The bed of the main channel is everywhere loose, coarse sand and is generally flat without an apparent thalweg. Bank slopes are also flat. Occasional steep sides seem to indicate a leveling of grade rather than depth of flow. Braiding (channel splits and rejoins) is common in the lower two-thirds of the main channel. The meander factor is 1.1, computed by comparing taped channel length to valley length.

Dense brush (much of it dead) is common in the islands of the braids and along the channel sides. In the upper third of the watershed, brush completely obscures the channel floor for distances of up to 100 ft. Sparse weeds 18 in. tall are also common, particularly in the lower reaches. Simons and Li (1982) indicates that Manning's n for the channels should be 0.030; it was increased to 0.035 to account for vegetation and trash.

In addition to the main channel, there are four significant tributaries. Of these the largest is the closest to the gage; it is 1200 ft long and 5 ft wide where it joins the main channel. The others are shorter and average about 2-1/2 ft wide. The tributaries are similar to the main channel: sudden appearance, flat, sandy beds, brush in and along channels. They are deeper for a given width, however, lack braiding, and are slightly steeper.

Smaller still are the channels at the bottom of swales. Flow obviously occurs here but there is no distinct sandy-bottomed bed. Vegetation at the soil line is sparse enough that flow is not greatly impeded, though the roughness is greater than in the main channel. Many places in the watershed, the ruts of the east-west dirt roads function as channels; the ruts are fairly smooth and have an effective combined width of about 5 ft. The average ridge-to-channel length is 72 ft.

Soils

The soil is Embudo-Tijeras Complex (gravely, fine sandy loam) with about 50 percent Embudo series, 35 percent Tijeras, and 15 percent other (SCS, 1977). Embudo soils are deep, well-draining, alluvial soils derived from decomposed coarse-grained granitic rocks. Permeability is described as moderate in the upper 20 in. (0.6 to 2.0 in/hr) and very rapid (>20 in/hr) below. Embudo soils are nonplastic, nonswelling soils with approximately 25 percent by weight passing the #200 screen. They are found on slopes of 0 to 5 percent, frequently along the bottom of swales, and are moderately susceptible to erosion. Tijeras soils are similar, except for the presence of some clay in the upper 20 inches, permeability 2 to 20 in/hr below that, and the fact they are more often found along ridges. Slopes range from 1 to 9 percent. The surface of both soils is grainy, with large amounts of fine gravel (1/8 to 3/8 in.). The entire complex is hydrologic soil group B.

Vegetation

The vegetation throughout the watershed is primarily native grasses with some brush and occasional cactus. Cover density ranges from 30 to 45 percent, but is close to 40 percent throughout. Most of the grasses are 6 in. to 1 ft high and grow in clumps but some are less than 2 in. and grow in rings. The brush is low (2 to 5 ft) and typically occurs in dense thickets along or in the channels and in swales without well-defined channels. Wild gourd also grows along the channels. An occasional cholla cactus grows along the slopes, particularly in the higher elevations. For the purposes of the model, the entire watershed is classified as herbaceous.

Testing and Modification

To refine the estimate of initial infiltration rate and possibly to incorporate a long-term constant rate, infiltration tests were made at nine sites in the watershed. Each site was sampled for percent cover and a ponded test was run using a double ring infiltrometer. The chief advantage of this test are that it is inexpensive enough, simple enough, and portable enough to be used on a routine basis. In some tests, to simulate sealing from drop impact, the area was sprinkled from a garden watering can held 8 ft high. The rings, 12 and 18 in., were inserted approximately 3 in. into the soil, the grass was clipped to minimize interference with the readings, and the head was maintained at 1 in. To minimize the effect of turbulence, the measured water for the inner ring was poured into a perforated 2 in. can.

Rates after 1 minute ranged from 4.9 to 15.9 in/hr and averaged 11.2 in/hr. After the rates became constant (30 to 40 minutes) the range was 2.1 to 5.2 in/hr, averaging 3.7 in/hr. There was no identifiable trend due to prior sprinkling, although it may be presumed to lower the average rates. Since the maximum 5 minute intensity of storms with significant runoff is often less than 4 in/hr, these data say there should be no runoff whatsoever. Clearly these data are too far in error to be directly useful.

Infiltration rates were adjusted to the ranges given in Table 6 to provide reasonable consistency with the fact that runoff from moderate storms is observed. These rates, then, are not those computed from

Table 6

Infiltration Rates
North Camino Tributary

Soil Group	Initial Infiltration Rate (in/hr)
A	1.20-2.00
B	0.90-1.20
C	0.60-0.90
D	0.30-0.60

tests, but rather a judgment balancing high measurements from field study and lower estimates deduced from the runoff record.

It can be qualitatively concluded that the time of surface flow is a significant factor in the overall runoff process. In that the soil can rapidly infiltrate standing water, what runs off must make it to the channel quickly. Likewise, as channel infiltration rate is high, what leaves the watershed must do so rapidly.

Surface roughness was reduced to allow the more rapid surface runoff which must occur. Manning's n was estimated,

$$n = 0.07 + 0.05 \text{ (percent cover)}.$$

Precipitation

The model was tested for the storm of August 14, 1980, a storm exceeding 100-year rainfall over portions of Albuquerque. Rainfall data were supplied by the U.S. Geological Survey from the recording rain gage adjacent to the stream gage. The early morning storm lasted for 220 minutes and had a maximum intensity of 3.60 in/hr with a maximum intensity of 0.72 in/hr after 160 minutes. Total rain was 3.51 in. Rain data were taken only from the gage at the basin outlet since no other gage was closer to any part of the watershed.

The antecedent moisture condition for this storm was taken as 2, i.e., normal conditions.

Runoff

For the storm the USGS recorded a maximum flow rate of 131 cfs 95 minutes after the start of measurable rainfall. The watershed, described by 148 quadrants, was modeled for 180 minutes at 0.5 minute steps. Peak flow was 173 cfs at 97 minutes. The computed hydrograph, hyetograph, and measured points (as crosses) are shown in Figure 11. The Geological Survey figures for rainfall and time of peak flow are reliable, but the magnitude of peak flow is not. USGS records for this station are noted "poor"; a representative of the Albuquerque field office estimated actual flows might differ by ±40 percent. The major problem is the location of the stage gage, dictated more by practical/legal considerations than by hydraulic ones. The rating curve for the gage was established by a step-backwater analysis. Such a calculation is reasonably accurate, given a straight and uniform upstream channel and known roughness coefficient. Within 300 ft of this gage, the channel changes width dramatically, bends and rebends, has a growth of weeds and brush, and crosses two roads which contribute flow. Additionally, the gage tends to silt up during runoff. At small flows the stream may meander within the bed and miss the gage entirely.

It can be concluded that the model correctly predicts the runoff timing, and given the likely bias in the measurement, reasonably describes the magnitude of flow.

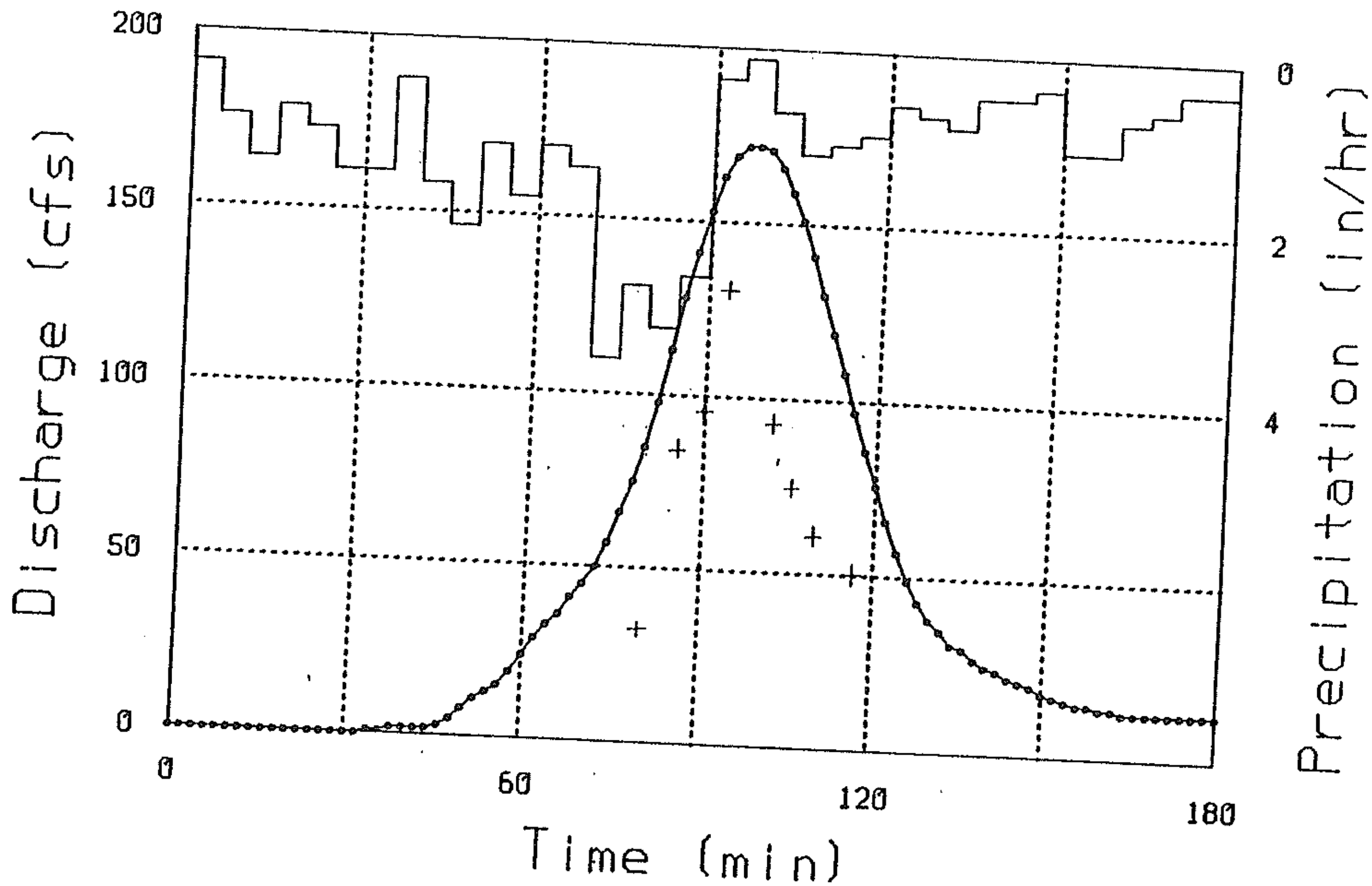

Figure 11. Hydrograph, North Camino tributary.

Discussion

It is unclear whether the antecedent moisture condition for this storm should have been 2 (normal) or 1 (dry). Gray, et al. (1982), suggest that over 80 percent of all storms occur under AMC 1. Hawkins (1977) back-calculated the amount of rain needed to shift from AMC 1 to 2 to 3 and suggested fractional AMC's. These considerations indicate that AMC 1 might have been appropriate, even though August is a month of frequent brief showers in Albuquerque. In trial runs checking the effect of various parameters, shifting from AMC 2 to AMC 1 reduced the maximum flow rate by approximately 10 percent.

In this model, antecedent moisture condition and the curve number approach are used to estimate surface infiltration by way of parameters for initial rate and maximum amount. This is an area where improvement is desirable but difficult even at the expense of major effort in data collection.

The model continues to be tested against lower flows of record on this watershed. Minor refinements may be necessary to get agreement with the data and with the August 14 storm. Two possible improvements, deal with the odd shape of this watershed. One is a more quadrant specific approach to stream order. The other is to make Manning's n vary with stream order; the effect of brush and trash is more pronounced in the smaller streams and smaller streams tend to not be hydraulically wide. In considering lower flows, it must be noted that the data probably are not as good, and that although deviation of 20 to

30 cfs are relatively major for low flows, it is generally the high flows that are of interest.

SUMMARY AND CONCLUSIONS

Summary

This study developed a computer model for rainfall runoff from watersheds of nonhomogeneous hydrologic characteristics. A quadrant-based watershed description allows elevation, soil and cover type, cover density and derived surface roughness and infiltration rate and capacity to be distributed in any manner. Elevation specification of each quadrant in turn defines the convergent pattern of the watercourses.

When rainfall occurs on a quadrant, the surface storage of that quadrant is increased. If there exists subsurface storage capacity, some or all of the surface storage may infiltrate. Of the unabstracted surface storage, some will flow into a channelized watercourse, adding to channel storage. Some or all the channel storage may infiltrate. Of that remaining, a portion will flow out of the quadrant into the channels downstream.

Simulation of watershed runoff is done in short time steps, allowing analysis of nonsteady fluid behavior by steady-state approximation. At each time step, quadrant states are summarized, providing a quasi-continuous description of the watershed's behavior.

The watershed model is not a perfectly generalized algorithm. There are numerous alternative equations for processes such as infiltration and surface flow. There are several programming modifications that may improve execution or input/output for specific cases. The user must modify the model to reflect special characteristics pertinent to an application.

Conclusions

The watershed model simulates rainfall runoff in a hydraulically-justified manner. The grid-based watershed configuration allows investigation of nonhomogeneous systems.

Modeling undertaken in this study has produced encouraging results. It appears that the model is a pragmatically-useful tool. The extent of application to this point has been limited. No conclusion concerning robust success can yet be drawn. The model has been made to work. With further testing and development, the model will improve.

The model contributes toward both an improved understanding of the hydrologic process and an improved capability to anticipate hydrologic behavior.

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APPENDICES

A. WATERSHED MODEL

B. PROGRAM ANNOTATION

C. VARIABLE LIST

D. INPUT FORMAT

E. PARTITIONING PROGRAM

APPENDIX A

WATERSHED MODEL

```
0001          DIMENSION E(30,30),SG(30,30),CG(30,30),ON(30,30),AS(30,30),MAP(30)
             1,MSYM(11),LABEL(10),PIN(100),TIN(100),SSYM(4),CSG(4),PCTSG(4),CCG(
             25),H(30,30),C(30,30),CTU(30,30),QIN(30,30),F(30,30),EA(4),PCTC(30,
             330),CN(30,30),CSYM(5),FMAX(30,30),F1(30,30),CN1(5,4),CN2(5,4),W(30
             4,30),PCTCG(5),T1(30,30),T2(30,30),T3(30,30),T4(30,30),T5(30,30),
             5T6(30,30)
0002          DATA MSYM/'0   ','1   ','2   ','3   ','4   ','5   ','6   ','7   ',
             1'8   ','9   ','    '/,MSTAR/'*   '/,SSYM/'A   ','B   ','C   ','D
             2 '/,CSYM/'DB  ','H   ','MB  ','JG  ','PP  '/,CN1,CN2/80.,77.,76.,7
             37.,65.,84.,84.,83.,84.,73.,90.,90.,90.,90.,83.,92.,93.,96.,93.,89.
             4,16.,36.,58.,66.,38.,08.,26.,46.,52.,32.,08.,18.,36.,34.,26.,03.,1
             50.,28.,10.,16./,IMIN,JMIN/2*100/,EMIN/1.E+10/
0003          EF1 = 1./3.
0004          EF2 = 2./3.
0005          EF5 = 5./3.
0006          READ(5,507) LABEL,AMC,TL,TM,XN,D,RU,R1,KU
0007    2     READ(5,501) I,J,E(I,J),SG(I,J),CG(I,J),PCTC(I,J)
0008          IF(E(I,J).LE.0.) GO TO 3
0009          COUNT = COUNT+1.
0010          IF(I.GT.IMAX) IMAX = I
0011          IF(I.LT.IMIN) IMIN = I
0012          IF(J.GT.JMAX) JMAX = J
0013          IF(J.LT.JMIN) JMIN = J
0014          IF(E(I,J).GT.EMAX) EMAX=E(I,J)
0015          IF(E(I,J).LT.EMIN) EMIN=E(I,J)
0016          DO 9 M=1,5
0017    9     IF(CG(I,J).EQ.CSYM(M)) MM=M
0018          DO 18 N=1,4
0019    18    IF(SG(I,J).EQ.SSYM(N)) NN=N
0020          CSG(NN)=CSG(NN)+1.
0021          CCG(MM)=CCG(MM)+1.
0022          CN(I,J)=CN1(MM,NN)-CN2(MM,NN)*PCTC(I,J)
0023          IF(AMC.LT.1.5.AND.CN(I,J).GT.85.) CN(I,J)=CN(I,J)*(0.0133*CN(I,J)
             1-0.333)
0024          IF(AMC.LT.1.5.AND.CN(I,J).LT.85.) CN(I,J)=CN(I,J)*(0.0053*CN(I,J)
             1+0.350)
0025          IF(AMC.GT.2.5.AND.CN(I,J).GT.40.) CN(I,J)=CN(I,J)*(-0.0083*CN(I,J)
             1+1.833)
0026          IF(AMC.GT.2.5.AND.CN(I,J).LT.40.) CN(I,J)=CN(I,J)*(-0.0217*CN(I,J)
             1+2.369)
0027          IF(SG(I,J).EQ.SSYM(1)) F1(I,J)=2.00+1.00*PCTC(I,J)
0028          IF(SG(I,J).EQ.SSYM(2)) F1(I,J)=1.20+ .80*PCTC(I,J)
0029          IF(SG(I,J).EQ.SSYM(3)) F1(I,J)= .70+ .50*PCTC(I,J)
0030          IF(SG(I,J).EQ.SSYM(4)) F1(I,J)= .30+ .40*PCTC(I,J)
0031          FMAX(I,J) = 1000./CN(I,J)-10.
0032          GO TO 2
0033    3     IOUT=I
0034          JOUT = J
```

```
      IF(E(IOUT-1,JOUT).GT.0.) GO TO 10
      IF(E(IOUT,JOUT-1).GT.0.) GO TO 11
      IF(E(IOUT,JOUT+1).GT.0.) GO TO 12
      ILAST = IOUT+1
      JLAST = JOUT
      GO TO 13
   10 ILAST = IOUT-1
      JLAST = JOUT
      GO TO 13
   11 ILAST = IOUT
      JLAST = JOUT-1
      GO TO 13
   12 ILAST = IOUT
      JLAST = JOUT+1
   13 IT=IMIN-1
      IB=IMAX+1
      JL=JMIN-1
      JR=JMAX+1
      READ(5,511) DT,TSIM
      DO 4 I=IT,IB
      DO 4 J=JL,JR
      IF(E(I,J).EQ.0.) GO TO 4
      EA(1) = E(I-1,J)
      EA(2) = E(I,J-1)
      EA(3) = E(I,J+1)
      EA(4) = E(I+1,J)
      IF(EA(1).EQ.0.) EA(1)=EA(4)
      IF (EA(4).EQ.0.) EA(4)=EA(1)
      IF (EA(2).EQ.0.)EA(2)=EA(3)
      IF (EA(3).EQ.0.) EA(3)=EA(2)
      A=0.
      EAT=0.
      DO 1 K=1,4
      IF(EA(K).EQ.0.) GOTO 1
      A=A+1
      EAT=EAT+ABS(EA(K)-E(I,J))
    1 CONTINUE
      AS(I,J) = EAT/A/D
      ON(I,J) = 0.1+0.1*PCTC(I,J)
      IF(AS(I,J).LT.0.06) ON(I,J)=1.15*ON(I,J)
      IF(AS(I,J).LT.0.03) ON(I,J)=1.13*ON(I,J)
      T1(I,J) = FMAX(I,J)/12.
      T2(I,J) = 1.-EXP(-F1(I,J)*DT/FMAX(I,J)/60.)
      T3(I,J) = DT*60.*SQRT(AS(I,J)/3.)/TL/ON(I,J)
      RD=D*SQRT(FLOAT(I-IOUT)**2+FLOAT(J-JOUT)**2)
```

```
      IF(RD.LT.RU) RD=RU
      IF(RD.GT.R1) RD=R1
      W(I,J)=D*10.**((1+(KU-1)*(R1-RD)/(R1-RU))/7.)/TL
      T4(I,J)=.7*D*IM*W(I,J)
      T5(I,J)=DT*60.*SQRT(AS(I,J))/.7/D/TM**1.5/XN
      T6(I,J)=DT/35.*SQRT(D*TM)
    4 CONTINUE
      E(IOUT,JOUT)=E(ILAST,JLAST)-AS(ILAST,JLAST)*D
      WRITE(6,513) LABEL,AMC,TL,TM,XN
      DO 7 I=IMIN,IMAX
      DO 7 J=JMIN,JMAX
      IF(I.EQ.IOUT.AND.J.EQ.JOUT) GOTO 7
      IF(E(I,J).EQ.0.) GO TO 7
      WRITE(6,502)  I,J,E(I,J),AS(I,J),SG(I,J),CG(I,J),PCTC(I,J),CN(I,J)
     1,FI(I,J),FMAX(I,J),LN(I,J),W(I,J)
    7 CONTINUE
      WRITE(6,510)ILAST,JLAST,IOUT,JOUT
      AREA = COUNT*D*D/43560.
      RANGE = (EMAX-EMIN+.01)/10.
      CI = 10./9.*RANGE
      DO 5 I=IMIN,IMAX
      DO 6 J=JMIN,JMAX
      K = IFIX((E(I,J)-EMIN)/RANGE)+1
      IF(E(I,J).EQ.0.) K=11
      IF(I.EQ.IOUT.AND.J.EQ.JOUT) K=11
    6 MAP(J) = MSYM(K)
    5 WRITE(6,504) I,(MAP(J),J=JMIN,JMAX)
      WRITE(6,509) (MSTAR,J=JMIN,JMAX)
      WRITE(6,508) (J,J=JMIN,JMAX)
      WRITE(6,503) LABEL,AREA,D,EMAX,EMIN,ILAST,JLAST,CI
      DO 22 I=IMIN,IMAX
   22 WRITE(6,504) I,(SG(I,J),J=JMIN,JMAX)
      WRITE(6,509) (MSTAR,J=JMIN,JMAX)
      WRITE(6,508) (J,J=JMIN,JMAX)
      DO 23 K=1,4
   23 PCTSG(K) = CSG(K)*100./COUNT
      WRITE(6,516) LABEL,D,(SSYM(K),PCTSG(K),K=1,4)
      DO 31 I=IMIN,IMAX
   31 WRITE(6,504) I,(CG(I,J),J=JMIN,JMAX)
      WRITE(6,509) (MSTAR,J=JMIN,JMAX)
      WRITE(6,508) (J,J=JMIN,JMAX)
      DO 30 K=1,5
   30 PCTCG(K)=CCG(K)*100./CCUNT
      WRITE(6,517) LABEL,D,(CSYM(K),PCTCG(K),K=1,5)
      NSIM = TSIM/DT + 1
```

```
      READ(5,511) TIN(1),PIN(1)
      DO 16 I=2,100
      II = I-1
      READ(5,511) TIN(I),PIN(I)
      IF(TIN(I).LT.TIN(II)) GO TO 21
16    CONTINUE
21    WRITE(6,514) LABEL,(TIN(I),PIN(I),I=1,II)
      T=-DT
      WRITE(6,512) LABEL
      DO 19 K=1,NSIM
      T=T+DT
      CS1=CS
      CS = 0.
      SS=0.
      FC1=0.
      FS1=0.
      IF(T.GT.TIN(II)) P=PIN(II)
      IF(T.GT.TIN(II)) GOTO 14
15    IF(T.LT.TIN(JP+1)) GOTO 14
      JP=JP+1
      P=PIN(JP)
      GOTO 15
14    PI=P*DT/60.
      PT = PT+PI
      DO 20 I=IT,IB
      DO 20 J=JL,JR
      QIN(I,J) = QTO(I,J)
20    QTC(I,J) = 0.
      QTC(IOUT,JOUT) = 0.
      DO 17 I=IMIN,IMAX
      DO 17 J=JMIN,JMAX
      IF(E(I,J).EQ.0.) GO TO 17
      IF(I.EQ.IOUT.AND.J.EQ.JOUT) GOTO 17
      HT=H(I,J)+PI/12.
      IF(HT.EQ.0.) FS=0.
      IF(HT.EQ.0.) GOTO 50
      FS=(T1(I,J)-F(I,J))*T2(I,J)
      IF(FS.LT.0.) FS=0.
      IF(FS.GT.HT) FS = HT
50    HT=HT-FS
      FS1=FS1+FS
      F(I,J)=F(I,J)+FS
      IF(HT.EQ.0.) H(I,J)=0.
      IF(HT.EQ.0.) GOTO 51
      H(I,J)=(1./HT**EF2+T3(I,J))**(-1.5)
      IF(H(I,J).LT.0.) H(I,J)=0.
      IF(H(I,J).GT.HT) H(I,J)=HT
51    SS=SS+H(I,J)
```

```
      C(I,J) = C(I,J)+(HT-H(I,J))*D*D+QIN(I,J)
      IF(C(I,J).EQ.0.) FC=0.
      IF(C(I,J).EQ.0.) GOTG 52
      FC=T6(I,J)*SQRT(C(I,J))
      IF(FC.LT.0.) FC=0.
      IF(FC.GT.C(I,J)) FC=C(I,J)
   52 C(I,J)=C(I,J)-FC
      FCI=FCI+FC
      IF(C(I,J).EQ.0.) OUT=0.
      IF(C(I,J).EQ.0.) GOTO 53
      OUT=C(I,J)-T4(I,J)*((T4(I,J)/C(I,J))**EF2+T5(I,J))**(-1.5)
      IF(OUT.LT.0.) OUT=0.
      IF(OUT.GT.C(I,J)) OUT=C(I,J)
   53 CS=CS+C(I,J)
      C(I,J)=C(I,J)-OUT
      A1 = 0.
      A2 = 0.
      A3 = 0.
      A4 = 0.
      IF(E(I,J).GT.E(I-1,J).AND.E(I-1,J).GT.0.)  A1=E(I,J)-E(I-1,J)
      IF(E(I,J).GT.E(I,J-1).AND.E(I,J-1).GT.0.)  A2=E(I,J)-E(I,J-1)
      IF(E(I,J).GT.E(I,J+1).AND.E(I,J+1).GT.0.)  A3=E(I,J)-E(I,J+1)
      IF(E(I,J).GT.E(I+1,J).AND.E(I+1,J).GT.0.)  A4=E(I,J)-E(I+1,J)
      AT = A1+A2+A3+A4
      QTC(I-1,J) = QTC(I-1,J)+OUT*A1/AT
      QTC(I,J-1) = QTO(I,J-1)+OUT*A2/AT
      QTC(I,J+1) = QTO(I,J+1)+OUT*A3/AT
      QTC(I+1,J) = QTC(I+1,J)+OUT*A4/AT
   17 CONTINUE
      QOUT = QTO(IOUT,JOUT)/DT/60.
      HOUT = HOUT+QTO(IOUT,JOUT)*12./COUNT/D/D
      FST=FSI*12./COUNT+FST
      SS=SS*12./COUNT
      FCT=FCI*12./COUNT/D/D+FCT
      CS=CS*12./COUNT/D/D
   19 WRITE(6,515) K,T,P,PI,PT,FST,FCT,SS,CSL,HOUT,QOUT
      STCP
```

```
0209      501   FORMAT(2I5,F5.0,2A4,F5.0)
0210      502   FORMAT(2I4,F9.2,F8.4,3X,2A4,F5.2,F6.1,2F6.2,F7.3,F7.2)
0211      503   FORMAT(///' ELEVATION MAP OF ',10A4//' AREA =',F8.2,' ACRES',7X,
               1'QUAD WIDTH =',F7.2,' FT'//' EMAX =',F8.2,' FT',10X,'EMIN =',F8.2,
               2' AT (',I2,',',I2,')'//' CONTOUR INTERVAL =',F8.2,' FT'/'1')
0212      504   FORMAT(//I4,' *     ',30A4)
0213      507   FORMAT(10A4/7F10.0,I10)
0214      508   FORMAT(/7X,30I4)
0215      509   FORMAT(//10X,30A4)
0216      510   FORMAT('0DISCHARGE FROM QUADRANT (',I2,',',I2,') TO QUADRANT (',I2
               1,',',I2,')'/'1')
0217      511   FORMAT(8F10.0)
0218      512   FORMAT('1HYDROLOGIC SIMULATION OF ',10A4//24X,'PRECIPITATION',10X,
               1'INFILTRATION',8X,'STORAGE',11X,'DISCHARGE'/11X,'TIME    INTENSITY
               2 INPUT    TOTAL    SURFACE CHANNEL    SURFACE CHANNEL      TOTAL     RA
               3TE'/' PERIOD    (MIN)    (IN/HR)    ',3('(IN)      (IN)',6X),'(IN)
               4(CFS)'/)
0219      513   FORMAT(' QUADRANT DATA FOR ',10A4/'0ANTECEDENT MOISTURE CONDITION'
               1,F3.0/'0OVERLAND TRAVEL LENGTH =',F7.2,' FT'/'0CHANNEL SINUOSITY F
               2ACTOR =',F7.2/'0CHANNEL ROUGHNESS =',F6.3/'0ROW COL    ELEV      AS
               3    SG    CG    POTC    CN     FI    FMAX     ON      W'/)
0220      514   FORMAT(' PRECIPITATION INPUT TO ',10A4/'0TIME (MIN)     INTENSITY (
               1IN/HR)'//(F8.2,10X,F8.2))
0221      515   FORMAT(I5,F10.2,F11.4,F8.4,3(F8.4,F10.4),F8.2)
0222      516   FORMAT(///' HYDROLOGIC SOIL GROUP MAP OF ',10A4//' QUAD WIDTH =',
               1F7.2,' FT'//4(' PERCENT SOIL GROUP ',A4,'=',F7.2/)/'1')
0223      517   FORMAT(///' COVER COMPLEX MAP OF ',10A4//' QUAD WIDTH =',
               1F7.2,' FT'//5(' COVER COMPLEX ',A4,'=',F7.2/)/'1')
0224            END
```

APPENDIX B

PROGRAM ANNOTATION

(Statement Number)--Remarks:

(1)	Dimensioning. Increase for larger grids.
(2)	Mapping symbols. Curve number limits from Table 1.
(3-5)	Constant exponents
(6-7)	General and quadrant input
(8)	End of quadrant check
(9-15)	Grid count and data ranges
(16-19)	Cover and soil group typing
(20-21)	Cover and soil group quadrant count
(22-26)	Curve number calculation
(27-30)	Infiltration rate calculation
(31)	Infiltration capacity calculation
(32)	Next quadrant
(33-34)	Gaging station quadrant
(35-48)	Discharge quadrant
(49-52)	Plotting boundaries
(53)	Duration input
(54-72)	Average surface slope. Interior elevation determines constant traverse boundary grade.
(73-75)	Surface roughness
(76-86)	Constants for subsequent use
(87)	Gaging station quadrant elevation
(88)	General output

APPENDIX B (continued)

PROGRAM ANNOTATION

(89-94)	Quadrant description output
(95)	Discharge and gaging station quadrants
(96)	Basin area
(97-108)	Elevation map, 10 divisions
(109-112)	Soil group map
(113-115)	Soil group percentage
(116-119)	Cover group map
(120-122)	Cover group percentage
(123)	Simulation steps
(124-129)	Hyetograph input
(130)	Hyetograph output
(131-134)	Start simulation time step
(135-138)	Zero cumulators
(139-146)	Precipitation in time step
(147-151)	Channel inflow from previous time step updated and cumulator zeroed
(152-153)	Quadrant to be evaluated
(154-155)	Skip non-watershed and gaging station quadrants
(156)	Add precipitation to surface water
(157-161)	Surface infiltration
(160-164)	Subtract surface infiltration and add to cumulator and sub-surface storage
(165-169)	Final surface storage
(170)	Add surface storage to cumulator

PROGRAM ANNOTATION

(171)	Add surface runoff and upstream channel outflow to channel storage
(172-176)	Channel infiltration
(177-178)	Subtract channel infiltration and add to cumulator
(179-183)	Channel outflow
(184-185)	Add channel storage to cumulator and subtract channel outflow
(186-198)	Partition channel outflow
(199)	Next quadrant
(200)	Convert volume to discharge
(201-205)	Convert volumes to depths
(206)	Time step output

APPENDIX C

VARIABLE LIST

A	Number of adjacent quadrants
A1,A2,A3,A4	Square of elevation difference with adjacent quadrants (ft^2)
AMC	Antecedent moisture condition (1, 2, or 3)
AREA	Watershed area (acres)
AS(I,J)	Average slope of quadrant I,J
AT	Sum of squared elevation differences (ft^2)
C(I,J)	Channel storage volume in quadrant I,J (ft^3)
CCG(N)	Count of cover groups of type CSYM(N)
CG(I,J)	Cover group of quadrant I,J (DB, H, MB, JG, or PP)
CI	Contour interval for elevation map (ft)
CN1(M,N)	Curve number for cover group M and soil group N at PCTCO = 0
CN2(M,N)	Curve number for cover group M and soil group N at PCTCO = 1
CN(I,J)	Curve number corrected for AMC for quadrant I,J
COUNT	Number of quadrants
CS	Channel storage volume (ft^3/in)
CSL	CS, last time step (in.)
CSG(N)	Count of soil groups of type N
CSYM(N)	Cover group symbol N
D	Quadrant width (ft)
DT	Time increment (min)
E(I,J)	Elevation of quadrant I,J (ft)

VARIABLE LIST

EA(N)	E of adjacent quadrant N (ft)
EAT	Sum of absolute elevation differences (ft)
EF1,EF2,EF5	1/3, 2/3, and 5/3
EMIN	Minimum E (ft)
EMAX	Maximum E (ft)
F(I,J)	Cumulative infiltration into quadrant I,J (ft)
F1(I,J)	Initial infiltration rate for quadrant I,J (in/hr)
FC	Channel infiltration (ft^3/in)
FC1	Channel infiltration subtotal (ft^3)
FCT	Cumulative FC (ft^3/in)
FMAX(I,J)	Infiltration capacity of quadrant I,J (in.)
FS	Surface infiltration (ft)
FS1	Surface infiltration subtotal (ft)
FST	Cumulative (ft/in)
H(I,J)	Surface storage volume on quadrant I,J (ft)
HOUT	Cumulative discharge from watershed (in.)
HT	Surface storage volume (ft)
I	Quadrant row
IB	Bottom row number for maps
ILAST	Row of quadrant from which watershed discharges
IMAX	Greatest row number in watershed
IMIN	Least row number in watershed

VARIABLE LIST

IOUT	Row of "gaging station" quadrant to which watershed discharges
IT	Top row number for maps
J	Quadrant
JLAST	Column of quadrant from which watershed discharges
JMAX	Greatest column number in watershed
JMIN	Least column number in watershed
JOUT	Column of "gaging station" quadrant to which watershed discharges
JP	Precipitation intensity increment
JR	Right column number for maps
KU	Highest channel order
LABEL	Title of data set
MAP(J)	Map symbol for column J
MSTAR	* for maps
MSYM(K)	Map symbol K
NSIM	Number of time steps in simulation
ON(I,J)	Overland hydraulic roughness of quadrant I,J (Manning's)
OUT	Volume discharged from quadrant in time increment (ft^3)
P	Precipitation intensity (in/hr)
PCTC(I,J)	Cover decimal of quadrant I,J
PCTCG(K)	Percent of quadrants having CSYM(K)
PCTSG(K)	Percent of quadrants having CSG(K)
PI	Precipitation volume in time increment (in.)

VARIABLE LIST

PIN(I)	Precipitation intensity at TIN(I) (in/hr)
PT	Cumulated precipitation volume (in.)
QIN(I,J)	Volume of channel inflow to quadrant I,J from adjacent quadrants and quadrant surface (ft^3)
QOUT	Discharge from watershed (cfs)
QTO(I,J)	Volume of channel discharge to quadrant I,J from adjacent quadrants (ft^3)
RANGE	(EMAX - EMIN)/10
RD	Distance from quadrant to IOUT, JOUT
RU	Distance from gaging station to highest order channel arc (ft)
R1	Distance from gaging station to first order channel arc (ft)
SG(I,J)	Soil group of quadrant I,J (A, B, C, or D)
SS	Surface storage volume (ft/in)
SSYM(N)	Soil group symbol N for soil may
T	Time (min)
T1(I,J)	FMAX(I,J) (ft)
T2(I,J)	Proportional surface infiltration capacity for quadrant I,J
T3(I,J)	Change in $H(I,J)^{-2/3}$ ($ft^{-2/3}$)
T4(I,J)	Channel area in quadrant I,J (ft^2)
TS(I,J)	Change in $H(I,J)^{-2/3}$ ($ft^{-2/3}$)
T6(I,J)	Proportional channel infiltration for quadrant I,J
TIN(I)	Time at start of precipitation intensity (min)

VARIABLE LIST

TL	Overland travel length to channel (ft)
TM	Channel sinuosity factor (channel length/valley length)
TSIM	Duration of simulation (min)
W(I,J)	Channel width in quadrant I,J (ft)
XN	Channel hydraulic roughness (Manning's)

APPENDIX D

INPUT FORMAT

Title Card

Title of data set (col 1-40)

Second Card

Antecedent moisture condition, 1, 2, or 3 (col 1-10)
Average length of overland flow until runoff enters a well-defined channel, ft (col 11-20)
Channel sinuosity factor (channel length/downhill distance) (col 21-30)
Channel hydraulic roughness, Manning's (col 31-40)
Quadrant width, ft (col 41-50)
Distance, outflow to first order channel, ft (col 51-60)
Distance, outflow to highest order channel, ft (col 61-70)
Highest channel order (col 71-80, left justified)

Card for Each Quadrant in Watershed

Row (col 1-5, left justified)
Column (col 6-10, left justified)
Elevation of quadrant midpoint, ft (col 11-15)
Hydrologic soil group A, B, C, or D (col 16)
Vegetative cover complex, DB = desert brush, H = herbaceous, MB = mountain brush, JG = juniper-grass, PP = ponderosa pine (col 20-21)
Vegetative cover density, 0-1 (col 24-27)

Card for Location of Watershed Discharge (Gaging Station)

Row (col 1-5, left justified)
Col (col 6-10, left justified)

Time Card

Size of time step in analysis, min (col 1-10)
Length of analysis, min (col 11-20)

Card for Each Segment of Storm

Time at start of segment, min (col 1-10)
Precipitation intensity during segment, in/hr (col 11-20)

Blank Card

To signify end of storm

APPENDIX E

PARTITIONING PROGRAM

```
10 L = 40:D = 500
20  DIM X(100),Y(100),X1(5),Y1(5),A(5),E(4)
30  FOR I = 0 TO 4: READ E(I): NEXT
40  DATA    100,80,90,70,100
50 AX = (E(2) + E(4) - 2 * E(0)) / 2 / D / D
60 AY = (E(1) + E(3) - 2 * E(0)) / 2 / D / D
70 BX = (E(4) - E(2)) / 2 / D
80 BY = (E(1) - E(3)) / 2 / D
90  PRINT "AX = ";AX; TAB( 20)"BX = ";BX
100  PRINT "AY = ";AY; TAB( 20)"BY = ";BY
110 XS =  - BX * 1E10: IF AX <  > 0 THEN XS =  - BX / 2 / AX
120 YS =  - BY * 1E10: IF AY <  > 0 THEN YS =  - BY / 2 / AY
130  PRINT "XS = ";XS; TAB( 20);"YS = ";YS: PRINT
140 EN = E(0):KN = 1
150  FOR I = 1 TO 4
160  IF E(I) = EN THEN KN = KN + 1
170  IF E(I) < EN THEN EN = E(I):KN = 1
180  NEXT I
190  ON KN GOTO 200,220,240,270,320
200  IF E(0) = EN THEN MN = 0: GOTO 900
210  GOTO 330
220  IF E(0) > EN THEN 330
230  FOR I = 1 TO 4: IF E(I) = EN THEN MN = I: GOTO 900: NEXT

240  IF E(1) > EN AND E(3) > EN THEN MN = 0: GOTO 900
250  IF E(2) > EN AND E(4) > EN THEN MN = 0: GOTO 900
260  GOTO 350
270  IF E(1) > EN THEN MN = 3: GOTO 900
280  IF E(2) > EN THEN MN = 4: GOTO 900
290  IF E(3) > EN THEN MN = 1: GOTO 900
300  IF E(4) > EN THEN MN = 2: GOTO 900
310  GOTO 350
320 MN = 0: GOTO 900
330  IF E(1) >  = E(0) AND E(3) >  = E(0) AND E(2) < E(0) AND
     E(4) < E(0) THEN A(4) = D * D / 2 - XS * D:A(2) = D * D /
     2 + XS * D: GOTO 910
340  IF E(1) < E(0) AND E(3) < E(0) AND E(2) >  = E(0) AND E(4
     ) >  = E(0) THEN A(1) = D * D / 2 - YS * D:A(3) = D * D /
     2 + YS * D: GOTO 910
350  FOR J = 1 TO 4
360 X1(J) = ( - 1) ^  INT (J / 2) * D / 2
370 Y1(J) = ( - 1) ^  INT (J / 2 - .5) * D / 2
380  NEXT J
390 X1(0) = X1(4):Y1(0) = Y1(4)
400 X1(5) = X1(1):Y1(5) = Y1(1)
410  FOR J = 1 TO 4
420  FOR I = 0 TO N:X(I) = 0:Y(I) = 0: NEXT
430 X(1) = X1(J):Y(1) = Y1(J)
440 N = 1
450 N = N + 1
460 SX = 2 * AX * X(N - 1) + BX
470 SY = 2 * AY * Y(N - 1) + BY
480 RX =  SQR (SY ^ 2 + SX ^ 2)
490  IF RX = 0 THEN GY = ( - 1) ^  INT (J / 2 + .5):GX = GY *
     ( - 1) ^ (J + 1):DX = GX * L / 10:DY = GY * L / 10: GOTO
     520
```

```
500 DX = SX * L / RX
510 DY = SY * L / RX
520 X(N) = X(N - 1) + DX:Y(N) = Y(N - 1) + DY
530  IF AX > 0 OR AY > 0 THEN 570
540  IF (X(N) - XS) ^ 2 + (Y(N) - YS) ^ 2 > L ^ 2 THEN 570
550 N = N + 1:X(N) = XS:Y(N) = YS
560 KK = 1:M1 = 1:M2 = 0: GOTO 660
570 LF = 0
580  IF  ABS (Y(N)) - D / 2 > LF THEN LF = ( ABS (Y(N)) - D /
     2) /  ABS (DY)
590  IF  ABS (X(N)) - -D / 2 > LF THEN LF = ( ABS (X(N)) - D /
     2) /  ABS (DX)
600 X(N) = X(N) - DX * LF:Y(N) = Y(N) - DY * LF
610  IF LF = 0 THEN 450
620 M3 =  - 1
630  IF X(N) =  - X(1) THEN M3 = 1
640 M1 =  - M3 * ( - 1) ^ J
650 M2 = (M1 - 1) / 2
660 N = N + 1
670 X(N) = X1(J + M1):Y(N) = Y1(J + M1)
680 OUT = J + M2: IF OUT = 0 THEN OUT = 4
690 X(0) = X(N):Y(0) = Y(N)
700 X(N + 1) = X(1):Y(N + 1) = Y(1)
710 AR = 0
720  FOR I = 1 TO N
730  PRINT X(I); TAB( 25);Y(I)
740 AR = AR + X(I) * (Y(I + 1) - Y(I - 1))
750  NEXT I
760 AR =  ABS (AR) / 2:A(OUT) = A(OUT) + AR
770  PRINT "AREA = ";AR;"   OUT = ";OUT: PRINT
780 TA = TA + AR
790  NEXT J
800  IF KK = 0 THEN 860
810 A(5) = A(1)
820  FOR J = 1 TO 4
830 A(J) = A(J) +  ABS ((1 - ( - 1) ^ J) * (XS - X1(J + 1)) +
     (1 + ( - 1) ^ J) * (YS - Y1(J + 1))) * D / 4 - A(J + 1)
840  NEXT J
850  GOTO 910
860 EN = E(1):MN = 1
870  FOR I = 2 TO 4
880  IF A(I) = 0 AND E(I) <  = EN THEN EN = E(I):MN = I
890  NEXT I
900 A(MN) = D * D - TA
910  FOR I = 0 TO 4
920 P = A(I) / D / D
930  IF P < .001 THEN P = 0
940  PRINT I;" ELEV ";E(I); TAB( 20);"PCT = ";P
950  NEXT
```