A COMPUTER MODEL OF RAINFALL RUNOFF FROM A SYSTEM OF MULTIPLE WATERSHEDS

Ruh-Ming Li
Brent E. Spronk
Daryl B. Simons

ABSTRACT

Due to increasing interest in water resource planning, many computer models have been developed to simulate rainfall-runoff relationships. A useful model for predicting this response from watershed and river systems should meet the following criteria: (1) Spatial resolution should be flexible. Management plans and activities are often limited to small watersheds, however, many watersheds are large and often encompass complete river basins or sub-basins. Consequently, the spatial resolution should accommodate both small watersheds and complete river systems. (2) Methodology should be widely applicable. Although model parameters may be area specific, the model should provide a general cause-effect relationship between management practice and watershed response. (3) Sensitivity to management activities should be included in model development. It must be possible to represent management activities and simulate the resulting system response.

A computer model to simulate rainfall-runoff response from large watersheds was developed. In this model, a large watershed is divided into response units consisting of analytical infiltration and water routing routines. Each geometrical component of the large watershed is represented as an "open book" or Wooding plane watershed. Hydrographs simulated by each of these units is combined by a numerical kinematic wave channel routing program to form the total basin response. Channel routing combined with spatially locating each response unit and timing the entry of hydrographs from response units to the channel constitute the linkage program. Only the basic physical processes of interception, infiltration, and water routing involved in the rainfall-runoff relationship are considered.

INTRODUCTION

Watersheds are subject to planned and unplanned changes that affect the quality of the environment. A change in land use, management practices, or the occurrence of a natural disaster, such as a fire, may beneficially or adversely alter the natural environment. Management of watersheds requires quantitative predictions of these effects. The necessity for predicting the response of a watershed has led to the development of many hydrologic models for simulating water yields.

A watershed is an extremely complicated natural system that cannot be completely modeled. However, models representing the major hydrologic processes can be applied under a variety of conditions to predict effects of land use changes on watersheds.

The applicability of available mathematical models is often limited by the size of the study area. Because legal and social concern over a management activity usually encompasses a large area; a watershed model must be capable of evaluating effects of land treatment over an entire basin in order to be useful in management decision-making. Application of a simulation model to an entire basin requires subdividing the basin into small, homogeneous response units. A mechanism is then required for linking the smaller units together to simulate rainfall-runoff hydrographs from a system of multiple watersheds.

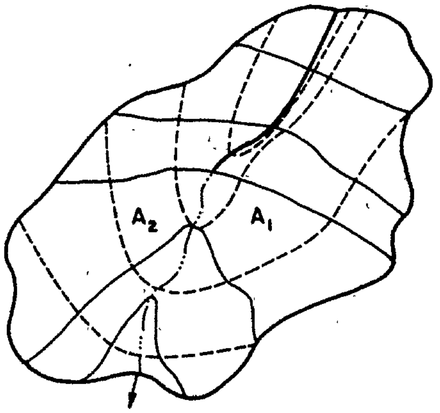
The Multiple Watershed Model (abbreviated as MULTWAT) was developed by Simons, Li, and Spronk (6) to simulate the rainfall-runoff relationship from large watersheds. MULTWAT is based on the Analytical Watershed Model (ANAWAT), that simulates storm runoff from small watersheds (5). MULTWAT provides a procedure for linking ANAWAT to a numerical kinematic wave channel counting program (4). This linkage gives MULTWAT the capability to model large watersheds. In addition, the hybrid solution utilizing both analytical and numerical methods provides a faster, more accurate and efficient mathematical model.

MODEL STRUCTURE

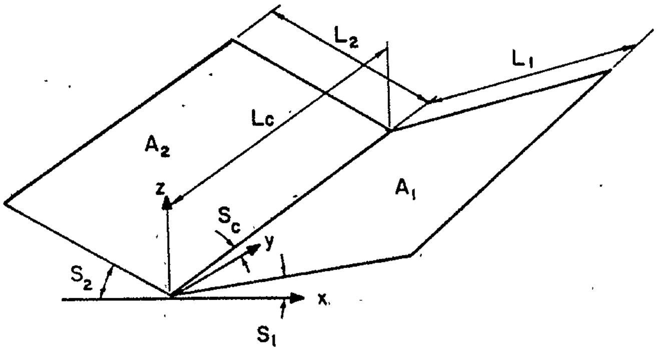
MULTWAT is designed to predict the storm water runoff from a system of multiple watersheds represented by ANAWAT units. Each ANAWAT unit determines the excess rainfall while considering the processes of interception and infiltration. Excess rainfall is routed by using the method of characteristic solution to the kinematic wave problem for overland and channel flow (5). ANAWAT has the capability of simulating the storm water runoff from a single plane or from the "open book" geometry first proposed by Wooding (8) and shown in Figure 1. MULTWAT classifies the single plane units as planes and the "open book" units as subwatersheds.

Storm water runoff hydrographs from the ANAWAT units serve as inputs to the interconnecting channel units. Water in the channels is routed by using a

FIGURE 1



(a) Original Subwatershed Topographic Map



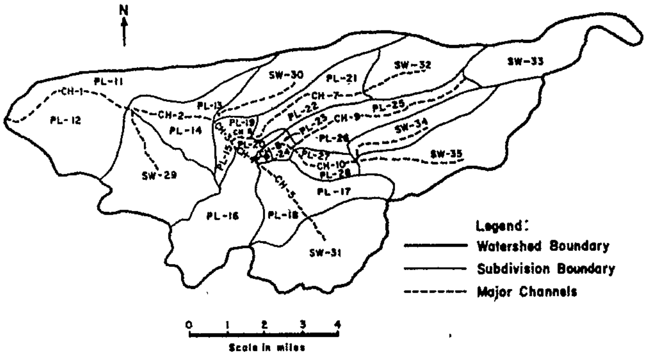
(b) Wooding Plane Representation

numerical solution to the nonlinear kinematic wave approximation. A method to account for channel losses due to infiltration is included in the channel routing procedure. The necessity of using a numerical channel routing routine rather than an analytical routine is due to the occurrence of kinematic shock as discussed by Kibler and Woolhiser (9). The analytical solution cannot be applied in situations where kinematic shock occurs.

There are four types of response units in MULTWAT: 1) a single plane ANAWAT unit, 2) an "open book" ANAWAT unit, referred to as a subwatershed, 3) a channel, which is a larger channel interconnecting the other units, and 4) a connection. A connection unit is used when only the lower part of a basin is being modeled and the response of the upstream portion of the basin is input as a hydrograph recorded at the gaging station dividing the upper and lower parts of the basin.

Because most large watersheds are nonhomogeneous in soils and vegetation, and have a complex topography, it is necessary to divide a large watershed into smaller units that are considered homogeneous and geometrically simple. Using a system of planes, subwatersheds and channels, MULTWAT can simulate the storm runoff from an entire basin. Figure 2 shows a map of Walnut Gulch, Arizona, a watershed selected for testing of the model. The boundaries of the planes and subwatersheds are marked to illustrate how a large watershed can be represented by a system of these units interconnected by channel units. Figure 3 shows a schematic diagram of Walnut Gulch Watershed, represented by planes, subwatersheds, and channels.

FIGURE 2



MODEL FORMULATION

The following assumptions were made for the model formulation:

1. Subwatersheds may be represented by an "open book" approximation (refer to Figure 1).
2. Soil characteristics are isotropic and homogeneous.
3. Canopy cover and ground cover are homogeneous.
4. Rainstorm events are spatially homogeneous and cover the entire plane or subwatershed unit.
5. Initial conditions such as soil moisture are uniform.
6. Evaporation processes are neglected for a single runoff event.
7. Streams within the watershed are ephemeral, and the movement of subsurface flow and groundwater flow are negligible.
8. The kinematic-wave approximation for flow routing is valid; i.e., the gradients due to local and convective accelerations are negligible and the water surface slope is nearly equal to the bed slope.
9. Water yield simulation is based on a single storm.
10. The stream channel geometry is stable; i.e., erosion and deposition of channel bank material is negligible.

The physical processes modeled for each type of unit are shown in Table 1. The processes involved in the plane and subwatershed units are identical except for the analytical channel routing performed for the subwatershed units. The only processes considered for the channel units are numerical routing and channel infiltration.

FIGURE 3

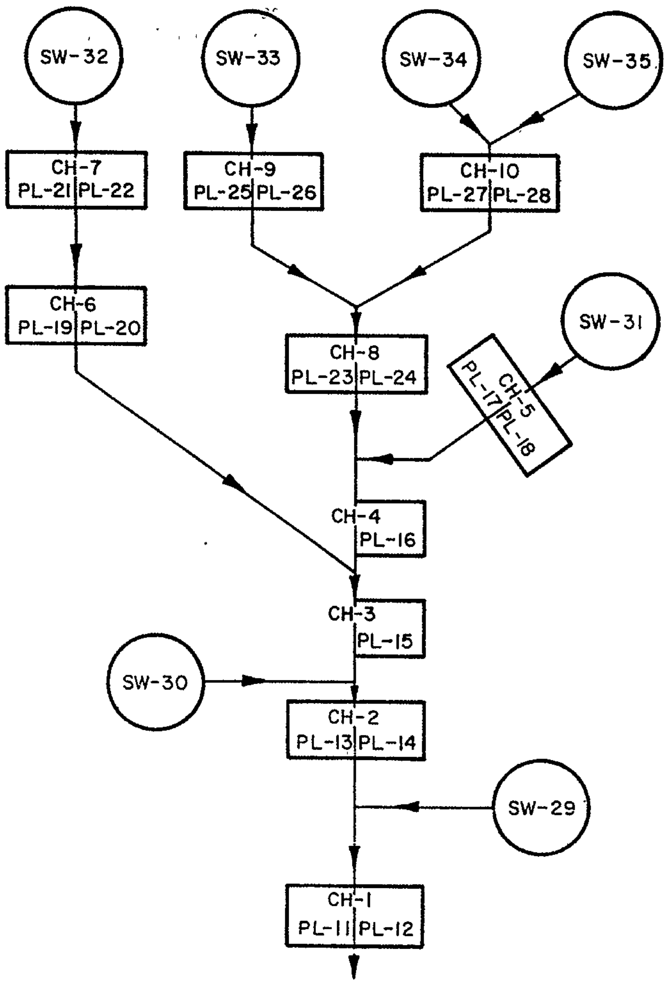


TABLE 1

	Plane	Subwatershed	Channel
Physical Processes Considered	1. Interception	1. Interception	1. Channel Infiltration
	2. Overland Infiltration	2. Overland Infiltration	2. Overland Channel Routing
	3. Analytical Overland Routing	3. Analytical Overland Routing	
		4. Analytical Channel Routing	

Much of the rain falling during the first part of a storm is intercepted by the vegetal ground cover. Precipitation intercepted by vegetation or other ground cover eventually evaporates, and the amount of rainfall reaching the soil surface is less than the recorded amount. The amount of interception loss depends on the percentage of the ground that is covered by canopy and ground cover, and their respective water holding capacities. The interception calculation used is identical to the approach used in the original ANAWAT (5). It is based on the assumption that interception starts at the beginning of a storm and continues until the potential intercepted volume is filled.

A portion of the rainfall reaching the ground moves through the soil surface into the soil. This process is defined as infiltration. The model used to simulate this process is based on the Green and Ampt infiltration equation (1). Development of the infiltration model is based on the following assumptions:

1. The effect of the displacement of air from soil has negligible effect on the infiltration process.
2. Infiltration may be regarded as purely vertical, and the movement of water through the soil may be described by a distinct piston wetting front.
3. Soil compaction due to rainfall impact is neglected.
4. Hysteresis effects in the saturation-desaturation process may be neglected.
5. Depth of overland flow is sufficiently small that it has little influence on the infiltration process.

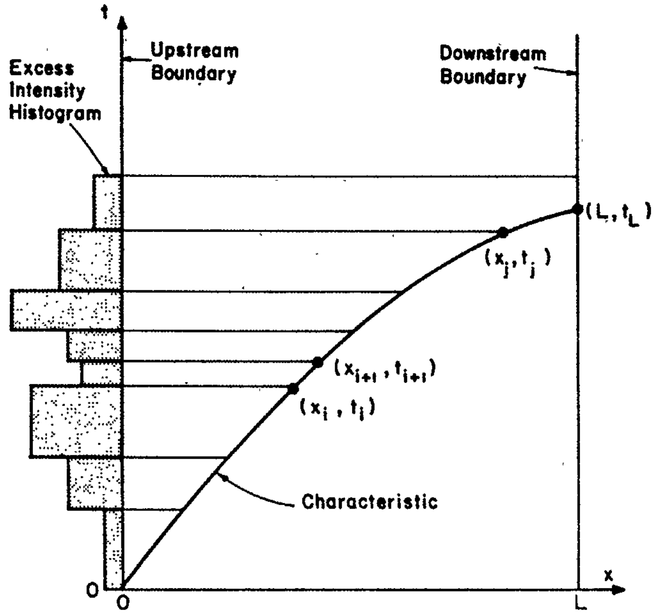
Using an explicit solution to the Green-Ampt equation given by Li, Stevens, and Simons (4), a function for infiltration with respect to time is developed. Thus, the infiltration occurring during a selected time period can be determined if the soil characteristics are known.

An analytical solution to the continuity, momentum, and cross section geometry equations is used to route water in the plane and subwatershed units. The method presented is identical to the routing scheme presented by Simons, Li, and Eggert (5). However, the routing of water with the condition of continuous infiltration is developed and incorporated. Due to the assumed "open book" geometry, both overland and channel routing are required. Excess rainfall, the amount of rainfall not intercepted or infiltrated, serves as the input to the overland flow routing scheme. Results of the overland flow routing are then used as the lateral inflow into either a subwatershed channel or a channel unit.

The partial differential equations for overland flow are solved by the method of characteristics. The characteristic paths along which the solution is valid, as shown in Figure 4, can be calculated in either the upstream or downstream direction. This allows a user to find the discharge at the downstream boundary for any given time.

A numerical procedure for water routing developed by Li, Simons, and Stevens (5) is used for the channel units. Routing is accomplished by a second-order nonlinear scheme developed to numerically solve the kinematic wave equation. A numerical routing procedure rather than an analytical procedure is used for the channel units because analytic solutions are restricted by the formation

FIGURE 4



of kinematic shock. Kinematic shock results when characteristic paths intersect. Physically this may be described as a faster moving parcel of water overtaking a slower moving parcel of water as they both travel downstream. Analytic solutions for problems that have kinematic shock display discontinuities in their hydrographs (9). Due to this restriction, a simple numerical routing procedure is necessary for the channel units.

Stability of a numerical procedure refers to whether the computational errors, due to the finite difference approximation of the partial differential equations, accumulate to an unbounded error. If the errors do not grow unbounded, the procedure is stable. The numerical scheme that is used has proved to be unconditionally stable and can be used with a wide range of time to space increment ratios without loss of significant accuracy (5). However, the physical significance of the time and space intervals should be considered when selecting their values.

An infiltration routine is combined with the numerical channel routing procedure to account for channel seepage losses. The channel infiltration procedure is similar to the overland infiltration procedure because both are based on the Green-Ampt infiltration equation (2). The major difference between the two routines is that the depth of the water in the channel situation cannot be neglected as in the overland situation.

Accuracy and reliability of watershed modeling is dependent on the quality and quantity of model input data. Watershed parameters needed to simulate the storm runoff are listed in Table 2. A more detailed description of these parameters is given by Simons, Li, and Spronk (6).

TABLE 2

I. Geometry
    1. Number of subdivisions
    2. Slope, length, and area for each plane and subwatershed unit
    3. Slope and length for channel units
    4. Relationships of: a) wetted vs. cross-sectional area and b) top width vs. cross-sectional area for each of the channel units

II. Soil Characteristics
    1. Effective hydraulic conductivity
    2. Porosity
    3. Initial and final soil moisture
    4. Average suction head
    5. Temperature
    6. Rilling ratio

III. Vegetative Cover
    1. Density
        a. Percent canopy cover
        b. Percent ground cover
    2. Cover Storage
        a. Canopy cover
        b. Ground cover

IV. Rainfall Data
    1. Rainfall hyetographs that are spatially constant over each subdivision

V. Overland Flow and Channel Flow Data
    1. Resistance to flow for each channel unit
    2. Resistance to flow for each subwatershed channel

VI. Outflow Hydrograph Criteria
    1. Duration of hydrograph
    2. Time increment used for the calculation of the hydrograph

DESCRIPTION OF THE COMPUTER PROGRAM

The program is divided into three main parts:
1) MULTWAT, the main program,
2) ANAWAT, the subrouting used to model subwatersheds and planes, and
3) CHANNEL, the subroutine used to model channels.

The main program for the simulation consists primarily of a sequence of calls to the ANAWAT and CHANNEL subroutines. The sequence of computations depends on the number of divisions of channels, planes, subwatersheds, and connection units made to a large watershed. The computing sequence has to follow the logic of gravity, hence upstream and lateral flow hydrographs for a particular channel can be calculated. The computational procedure must start by determining the outflow hydrograph of the "uppermost" channel in the basin and proceed to the downstream channel units until the outflow hydrograph of the basin is determined.

To follow the computational procedure in an orderly manner, the subunits of a large watershed are labeled as follows:

1) Channel units are labeled as CH-i where i is a number from 1 to k, and k is the total number of channel units. The channels are numbered starting with the lowest or downstream channel, then proceeding upstream. At a point where two or more channel units are connected the left most channel network is numbered first.

2) Plane units are labeled as PL-i where i is a number from k+1 to j, and j is the total amount of channel units plus plane units.

3) Subwatershed units are labeled as SW-i, where i is a number from j+1 to ℓ, and ℓ is the total number of channel, plane, and subwatershed units.

4) Connection units are labeled as CO-i, where i is a number from ℓ+1 to n, and n is the total number of units.

After the subunits of a watershed are properly labeled, a schematic diagram of the watershed is drawn. Referring back to Figures 2 and 3, an example of the above labeling scheme and a schematic diagram are shown for Walnut Gulch, Arizona. The diagram serves as a guide for determining the computational sequence. For example, the computational sequence for the diagram given in Figure 3 is given in Table 3. As shown in this table, the upstream lateral inflow units of a channel unit are a combination of planes, subwatersheds, and channels.

TABLE 3

Channel Unit	Upstream or Lateral Inflow Units
10	35, 34, 28, 27
9	33, 26, 25
8	24, 23, 10, 9
7	32, 22, 21
6	20, 19, 7
5	31, 18, 17
4	16, 8, 5
3	15, 6, 4
2	30, 14, 13, 3
1	29, 12, 11, 2

The flow chart for the main program, MULTWAT, is shown in Figure 5. Besides the sequence of calls to the ANAWAT and CHANNEL subroutines, the main program asks for the title of the watershed, the date of the storm, and the time interval and duration for the hydrograph to be simulated. After the computations are completed an output subroutine is called to display the results.

The ANAWAT portion of the program was originally developed by Simons, Li, and Eggert (6). The most current version of ANAWAT is essentially the same except for two important improvements. The program has a continuous infiltration routine and allows soil and vegetation parameters for each plane in the "open book" model to be different.

The subroutine ANAWAT is used to calculate the response hydrographs for either a subwatershed or plane unit. The subroutine consists of a series of calls to the physical process subroutines which determine input into the routing routines.

FIGURE 5

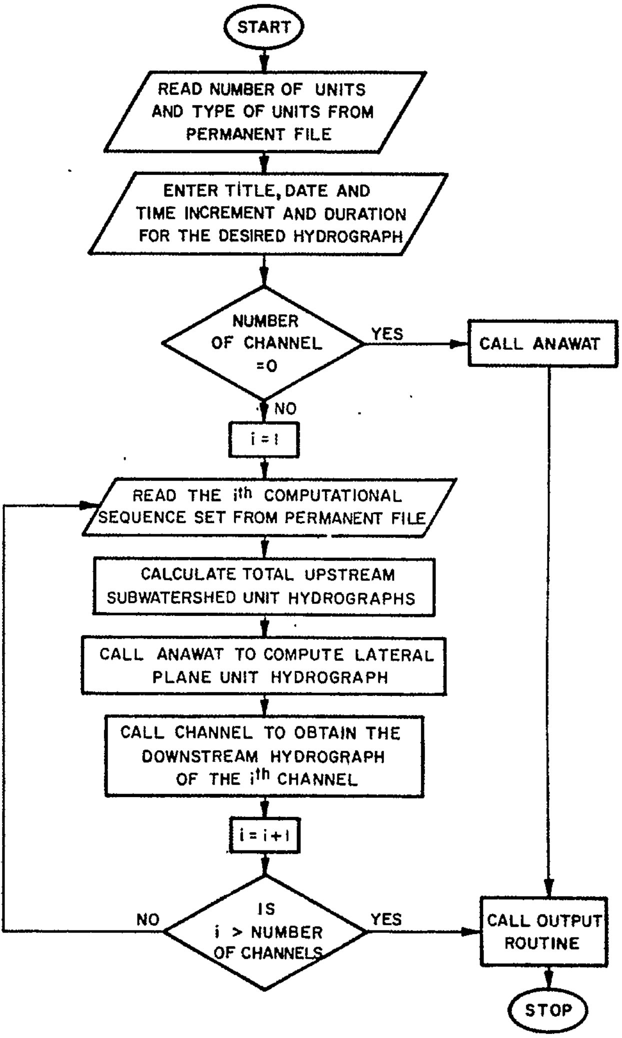


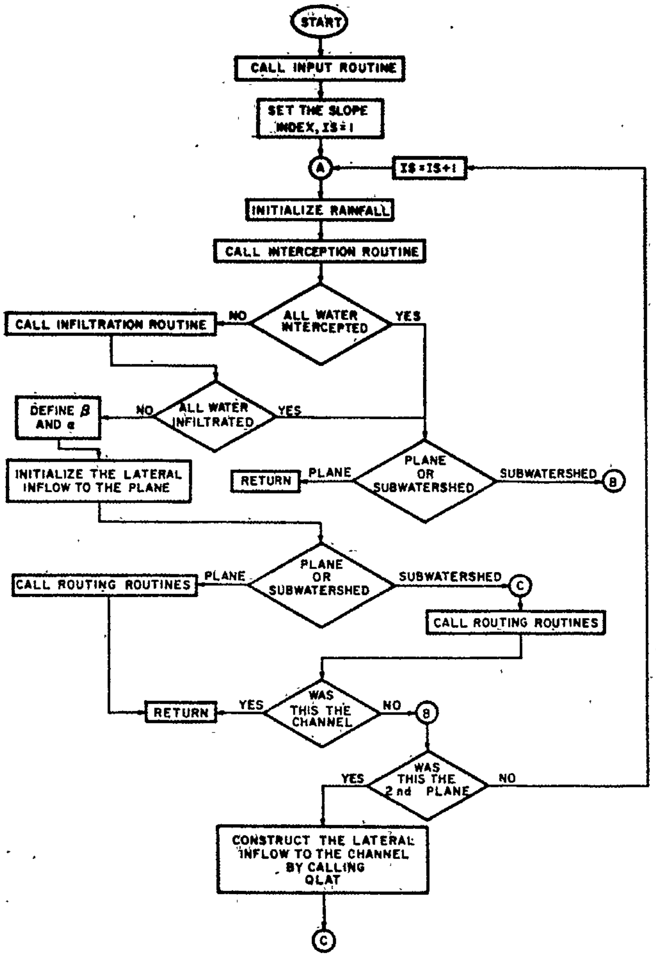
Figure 6 illustrates a flow chart for the ANAWAT routine.

The numerical channel routing scheme is much simpler to program than the analytical routing scheme used by the ANAWAT subroutine. The flow routing procedure for channels is identical to the numerical method proposed by Li, Simons, and Stevens (3). The only addition to the original scheme is that of the channel infiltration routine. The flow chart for the subroutine CHANNEL is shown in Figure 7.

MODEL TESTING AND APPLICATIONS

MULTWAT is a computer simulation of rainfall-runoff from a system of channels, planes, and subwatersheds representing a large, complex watershed. There are two types of model applications: 1) provide runoff hydrographs for ungaged watersheds and 2) aid in assessing changes in runoff hydrographs resulting from land use changes, management practices, or the occurrence of a natural disaster. These are referred to as data synthesis applications and management assessment applications, respectively.

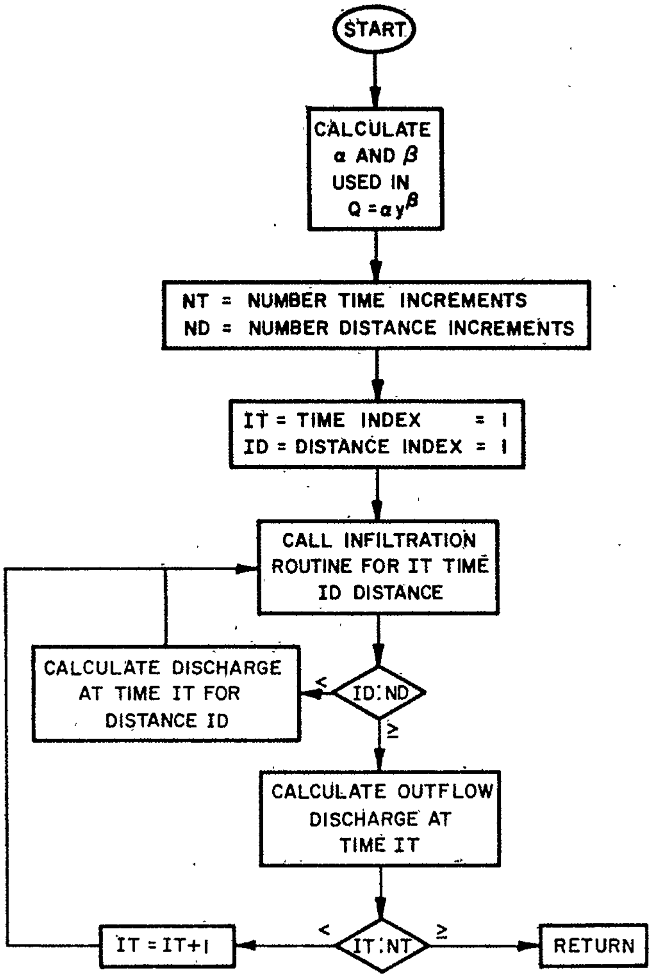
FIGURE 6



The watersheds used in the examples are located in Walnut Gulch, Arizona, which is operated by the U.S. Agricultural Research Service and surrounds the historic town of Tombstone, Arizona. The study area consists of 57.7 square miles of uncultivated semi-arid rangeland. Precipitation is measured with 93 recording rain gages spaced about evenly over the watershed. Runoff from the entire watershed and from nine subwatersheds is calculated from stage records collected at flow measuring flumes. The vegetation of Walnut Gulch consists of desert grasses and shrubs, and most of the soils are a gravelly loam. Seventy percent of the annual precipitation of 11.5 inches occurs during high intensity, short duration thunderstorms in the late summer months. These thunderstorms are quite variable in both time and space.

The watershed was divided using the techniques outlined by Simons, Li, and Spronk (6). They provide a method to obtain the watershed geometry using the U.S. Geological Survey topographical maps as the basic data source. The model parameters for Walnut Gulch are tabulated in Table 4. Except for the noted variations, these physical parameters remained constant for all storms.

FIGURE 7



The first four tests of the model used the portion of Walnut Gulch shown in Figure 8. The runoff from the six square miles is measured by flume No. 8 in the Walnut Gulch watershed. The upper .63 square miles of this area drains into a stock pond. It was assumed that spillage from the stock pond was small enough to be neglected. Hence, the drainage area for the stock pond was not included in the runoff analysis. Both small (30-50 cfs) and large (1000-2000 cfs) runoff events were modeled. Figure 9 shows a comparison of recorded and predicted runoff hydrographs at flume No. 8 for four different storm events. Agreement between the measured hydrographs and the simulated hydrographs is satisfactory.

The entire Walnut Gulch watershed (57.7 square miles) was modeled for three different storm events. The drainage areas (approximately 5.5 square miles) for several stock ponds were not included in the analysis since spillage was assumed to be negligible. The rainfall distributions for the response units were calculated by using an isohyetal map and individual gage records. The comparison of the predicted and recorded hydrograph is shown in

TABLE 4

	Overland Flow	Channel Flow
Hydraulic Conductivity[1]	.36-.38 in./hr	3.5-4.5 in./hr
Average Suction[2]	1.3 or 1.57 in.	1.6 or 2.0 in.
Porosity	0.50	0.50
Initial Soil Moisture[2]	.60 - .85	.50 - .85
Final Soil Moisture	1.0	1.0
Canopy Cover[1]	13.3% - 38%	NA
Canopy Cover Inter-Ception Value	0.05 in.	NA
Ground Cover	33%	NA
Ground Cover Inter-Ception Value	0.01 in.	NA
Temperature	70.0°F	NA
Rilling Ratio	0.12	NA
Resistance to Flow	0.053 (Darcy Wiesbach for subwatershed channels)	100 (Chezy C)

[1] These values vary spacially in the watershed. Range of variation is listed where applicable.

[2] Initial soil moisture conditions varied with storms. For cases when the initial soil moisture was equal or greater than .85, the lower value of average suction was used. This variation of average suction with initial soil moisture was shown by Eggert (1).

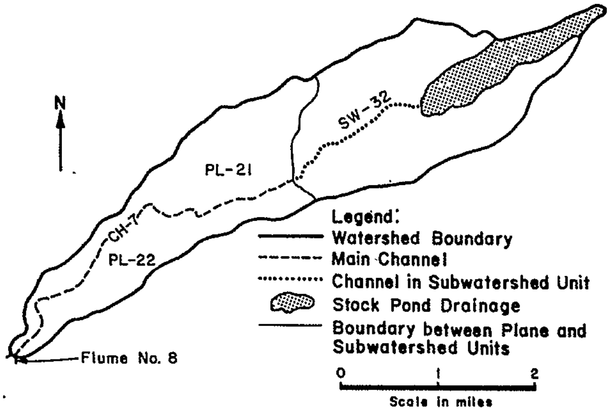
Figure 10. The agreement between predicted and recorded runoff is good considering the complexity and size of the watershed.

The following three examples illustrate how MULTWAT can be used to assess changes in rainfall-runoff due to land use changes, management activities, or a natural disaster. Because MULTWAT is based on the physical processes governing rainfall-runoff, it has the ability to reflect physical changes in the watershed environment. Figure 11 shows the comparison of the hydrographs for the undisturbed watersheds and the predicted assessment of the changed watersheds.

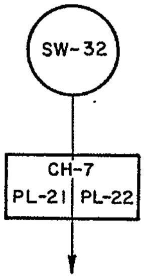
MANAGEMENT ASSESSMENT EXAMPLE (a)

This example illustrates change in runoff due to the removal of a stock pond located upstream of flume No. 8 in Walnut Gulch. The length of the upstream, subwatershed unit was increased to account for the drainage area from the stock pond. Figure 11a shows the effect of this change on the runoff hydrograph at flume No. 8 for the storm of September 4, 1965. The peak discharge and water volume were increased due to the increased drainage area.

FIGURE 8



(a) Portion of Walnut Gulch Watershed Used for Sensitivity Analysis.



(b) Schematic Representation.

FIGURE 9

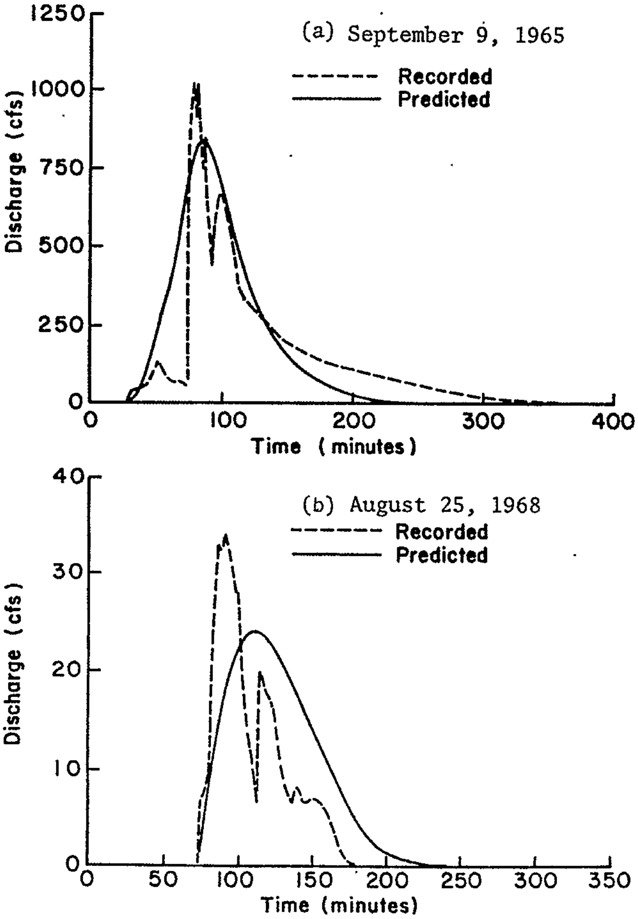


FIGURE 9 (continued)

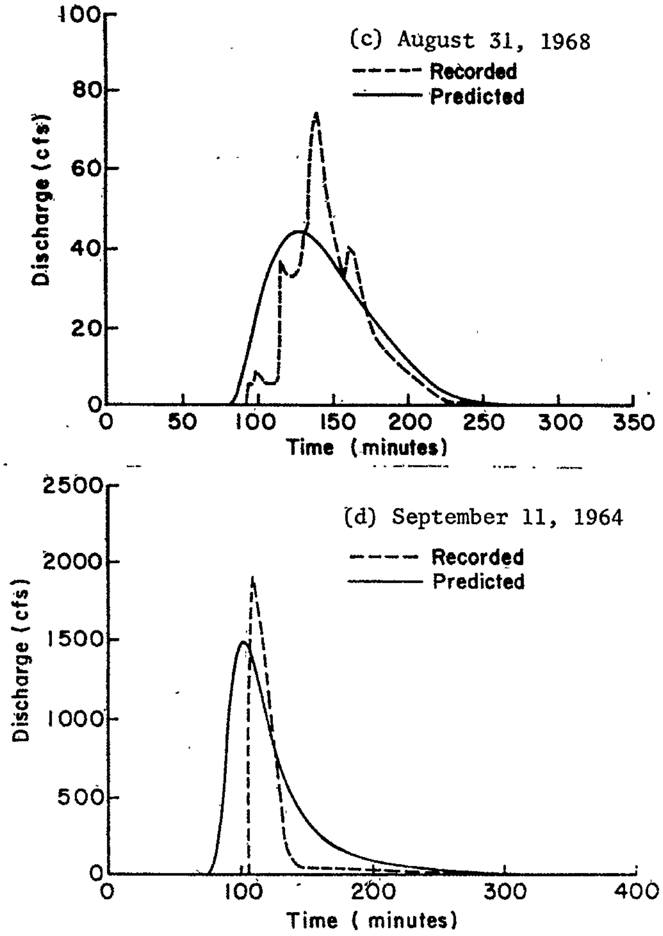
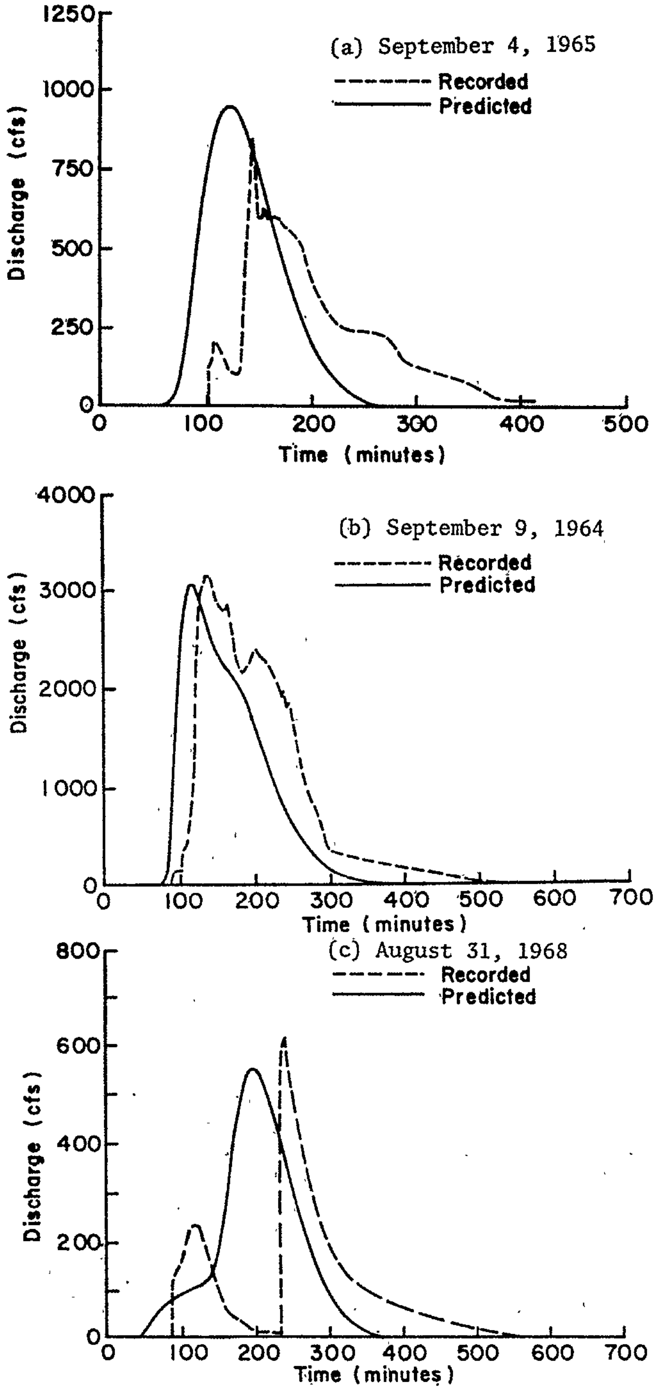


FIGURE 10



MANAGEMENT ASSESSMENT EXAMPLE (b)

The second example shows the effects of soil compaction due to mechanical site preparation for the drainage area above flume No. 8 at Walnut Gulch. The hydraulic conductivity was decreased from 0.36 to 0.30 inches per hour, and the porosity was changed from 0.50 to 0.40. The water runoff response was compared to the undisturbed watershed in Figure 11b for the storm of September 9, 1965. Results show a 50 percent increase in peak discharge and 35 percent increase in water volume.

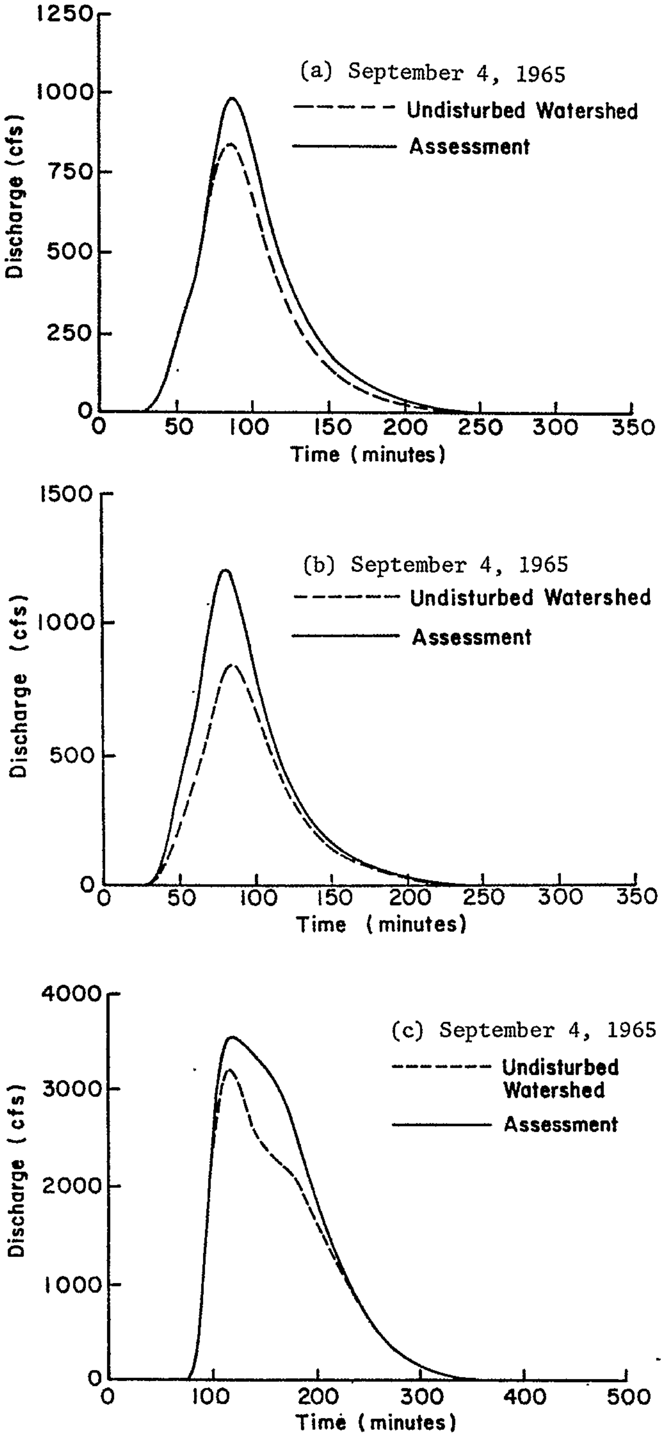
MANAGEMENT ASSESSMENT EXAMPLE (c)

The last example illustrates the change in runoff due to a fire on the upper portion of the Walnut Gulch watershed. A fire was estimated to remove all the canopy cover, reduce the ground cover from 33 to 25 percent, and reduce the hydraulic conductivity from 0.36 to .30 in./hr. These changes were applied to units SW34, SE35, PL27, PL28, SW33, PL25, PL26, and SW30 located in the upper portion of Walnut Gulch shown in Figure 2. The effect on the runoff hydrograph for the entire Walnut Gulch watershed for the storm of September 9, 1964 is shown in Figure 11c. The reduction in hydraulic conductivity and ground cover caused an increase in both the peak discharge and the water volume.

CONCLUSIONS

A deterministic watershed model to simulate rainfall-runoff relationships from large watersheds was demonstrated. This model is based upon a simplified geometry consisting of a system of planes, channels, and subwatershed "open-book" units. Test results show satisfactory agreement

FIGURE 11



between the simulated and recorded hydrographs. The watershed tested was Walnut Gulch, Arizona which consists of 58 square miles of semiarid rangeland. The results indicate the potential of the model to synthesize data for ungaged watersheds and to predict the response of watersheds to various types of management practices.

ACKNOWLEDGMENT

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