To the Graduate Council:

I am submitting herewith a thesis written by Vijay Kumar Srinivas entitled "Remote Sensing as a Tool in Regional Watershed Hydrology." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Engineering Science.

Ted Paludan

Ted Paludan, Major Professor

We have read this thesis and recommend its acceptance:

Fletcher N. Donaldson

Accepted for the Council:

Vice Chancellor
Graduate Studies and Research

REMOTE SENSING AS A TOOL IN REGIONAL WATERSHED HYDROLOGY

A Thesis
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ABSTRACT

This preliminary study was made to evaluate several facets of a watershed hydrology. The importance of watershed water resources management is briefed, and the application of remote sensing in several watershed environmental problems (relating to the hydrology of the region) enumerated. A brief discussion on the hydrologic processes and flood studies are outlined with illustrations. Two small watersheds (Fagan Creek and Upstream Aldridge Creek) in the vicinity of Huntsville, Alabama were selected for study. A brief discussion on the regional geology, soils and hydrology is included. Flood frequency estimations under urbanized conditions were made which generally indicated appreciable increase in runoff volume and peak discharges. A method for determining the average curve number based on a grid system is described.

The watershed physiographic parameters (channel slope, ground slope, etc.) were determined primarily from a United States Geological Survey/Tennessee Valley Authority (USGS/TVA) topographic map. The basic land use and land cover data derived from remotely sensed data (1:24,000 color infrared photography) were utilized to estimate the hydrologic parameters: percent of imperviousness, Soil Conserveration Service (SCS) curve number and Manning's roughness coefficient. These are

needed for input for several of the emperical and digital simulation models related to hydrology: flood frequencies, flood peak discharges, water pollution, etc.

The overall emphasis is on the methodology of utilizing remotely sensed data. A brief discussion on a hydrologic model is included, which constitutes an important tool in watershed hydrologic analysis. Preliminary estimates of peak discharges were made from sub-watersheds under estimated and hypothesized input conditions. Samples of "test" results are included.

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CHAPTER I

INTRODUCTION AND BACKGROUND

The hydrologic study of a watershed plays a significant role in effective watershed planning and management, specifically those related to urban land use and water resources. In a system sense, a watershed is a system in which the input (precipitation) is variable, but the output requirements are deterministic. While the water resources demands (municipal water supply, irrigation and hydroelectric power projects, etc.) are relatively fixed, the input factor (precipitation) is variable. This necessitates a balance between the two.

Two types of information vital to planners, hydrologists and water resource managers are:

1. Management information which deals with the response of the watershed to specific individual events. This information is required for the real-time optimization of supply versus demand, (e.g., day-to-day prediction of run-off for the management of water resources).

2. Planning information necessary to define the expected response of the watershed to statistically recurring peak events.

This information is needed for the optimal sizing of the waterworks, (e.g., estimation of storm runoff for the sizing and design of flood-control structures).

The term, watershed management, can be defined as the management of the natural resources of a drainage basin primarily for the production and protection of water supplies and water-based resources, including the control of erosion and floods, and the protection of esthetic values associated with water. Society of American Foresters, 1944 (Hewlett and Nutter, 1969).

Aspects involved in regional watershed study can be summarized as: (1) urban land use and hydrologic land use planning and management, (2) environmental monitoring, planning and management, (3) environmental impact assessment and analysis. The processes in a watershed are dynamic in nature and influenced by such regional factors as: precipitation, topography, geology, soil, land use and vegetative cover and the interaction between them.

A significant factor is the influence due to human activities on the watershed land surface which affects the behavior of some of the other factors with time.

The schematic diagram, as shown in Figure 1, gives a quick look at the complex ecological nature of watershed hydrology. In particular, the importance of environmental factors in watershed planning and management is vital for several reasons:

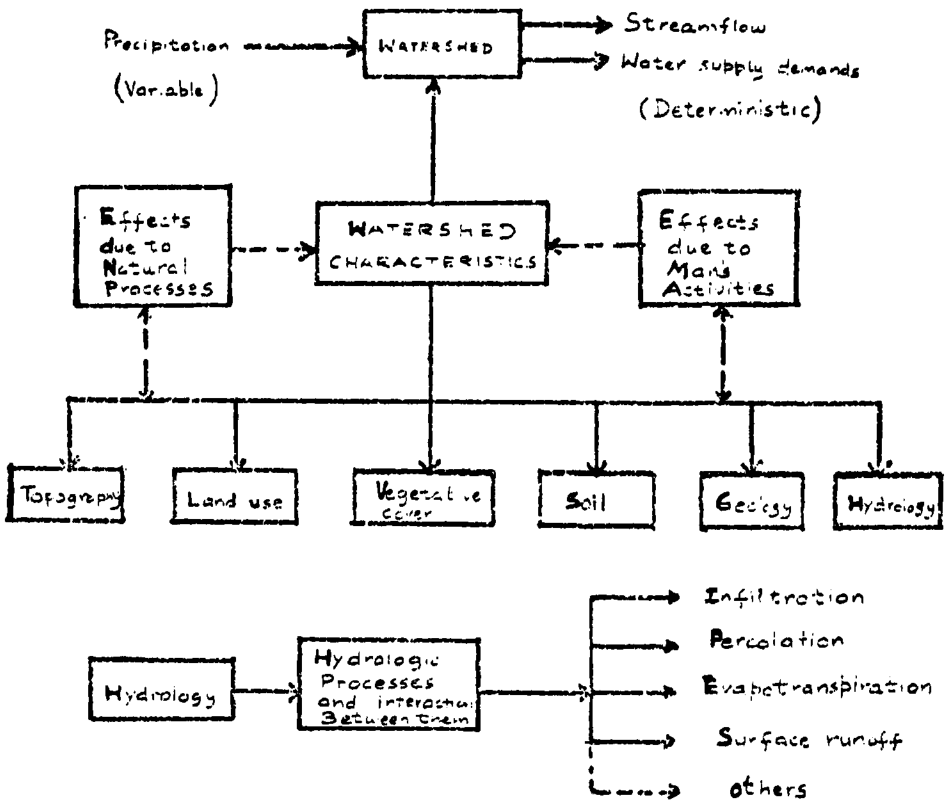


FIGURE 1. BLOCK SCHEMATIC OF WATERSHED HYDROLOGY.

1. To evaluate the present and projected water supply needs and consequent survey of potential water resources, both surface and ground water.

2. Study of the effects of urbanization on the watershed hydrological problems such as flooding, water quality, erosion and sedimentation in streams, etc.

3. Understanding the ecological and environmental effects of developments both in the upstream and downstream areas of the watershed.

Thus, the dynamic watershed processes result in significant changes in the Earth's natural systems and environment. Hence, based on ecological considerations any decision regarding environmental change should be made carefully. Enough geological, hydrological and biological facts should be considered to study the impact of changes on natural systems.

For example, construction projects like building of dams and canals, and utilization of ground water alters the natural water system. They meet part of the water supply demand and control the hazardous effects of floods. But they also result in environmental problems in both upstream and downstream areas of the watershed. For example, they can cause stream erosion and sedimentation, changes in evapotranspiration, etc.

Thus, there is a vital need for proper watershed management based on an understanding and research study of the complex nature of the interactions between the constituting factors. This is essential for sound management decisions towards the overall watershed development and also influence on the economy of the region.

Application of Remote Sensing in Regional Watershed Study

Remotely sensed data has been used in several environmental, urban land use and hydrologic problems in several regional watershed studies. Research study and projects conducted by different federal, state, local, and other private contractor agencies in the United States and elsewhere in the world have demonstrated the feasibility of using remotely sensed data. The results have indicated how remote sensing is a valuable tool in regional watershed monitoring, planning, and management.

The success of these projects has been largely facilitated due to the availability of remotely sensed data in different useful forms compatible with interpretation and anlysis techniques, both manual and computer-aided.

Multiple Choice of Sensor Data

Photographic cameras, multispectral scanners, radiometers, etc., each sensitive to different spectral regions in the electromagnetic spectrum, visible to microwave region, are available.

Data in Different Format

Data is available in both imagery and digital form which enables both manual methods and automatic classification and analysis techniques to be employed.

Different Analysis Techniques

Manual methods employ photointerpretation and need simple optical instruments: stereoscope, zoom transfer scope, etc. Digital data is compatible for analysis using a digital computer. Specific features of interest in the data can be enhanced by photographic, optical and digital methods (image processing).

In the study of this report the remotely sensed data generally refers to photographic data, from both aircraft and satellite platforms. The advantages of photographic imagery data in several watershed land use and environmental analysis have been well documented in several reports.

Areas in Which Remote Sensing Has Been Applied

1. Environmental analysis,
2. Soil Surveys, agriculture and related problems,
3. Geolgoical and mineral survey,
4. Land use and vegetative cover mapping,
5. Hydrology and water resources,
6. Special engineering projects.

Specific studies have been conducted relating to land, water, and air resources such as:

1. Monitoring urban land use and agricultural land use changes;

2. Effect of urbanization on water quality and frequency of flooding in an area;

3. Detecting sources of smoke plumes and determining the influence of air pollution on climate and weather.

Remote Sensing in Hydrology and Water Resources

The science of hydrology underlies watershed management, (Hewlett and Nutter, 1969). Applied hydrology is concerned with the inland (fresh) waters of the Earth, their occurrence, distribution, and circulation through the never-ending hydrological cycle. Hence, adequate information on, and a thorough understanding of, the hydrologic processes and hydrologic features will greatly contribute to better water resource management.

Remote sensing systems add the aerial dimension to the conventional hydrological data collected at point measurement stations. Further, many of the hydrologic features of interest are easily detected and measured with remote sensors (visible, infrared and microwave wavelengths). Thus, useful information has been gathered in hydrology, geohydrology and water resources. Some examples are as follows:

1. Inventory of surface water and survey for potential areas of groundwater, (e.g., study of geological lineaments);

2. Flood studies and floodplain management: Mapping flood inundated areas and estimating contribution of snow cover to expected runoff;

3. Monitoring water quality and water pollution of streams, lakes, reservoirs, etc.;

4. Analysis of watershed drainage and stream network systems.

Watershed Hydrology

Surface water systems are controlled by the nature of their watersheds. Remote sensing provides an effective scientific tool in monitoring the dynamics of a watershed, both due to natural processes and that due to Man's activities on the land surface (e.g., effect of urbanization on regional flood frequency and water quality).

The extensive hydrologic information that can be gathered (water resources, channel networks and drainage, hydrologic land use, etc.) are important for the watershed flood studies and problems related to water quality. Further, it assists in the planning for present and future water supply needs, construction of drainage sewers, flood detention projects, storage reservoirs, etc.

For an expected future development an estimate of the storm runoff volume and runoff rates (peak rates of discharge) can be made from information on the local climatic patterns, watershed characteristics, and other factors (e.g., soil-cover complex). Generally such predictions are made by applying empirical equations and mathematical models which are based on a historical data base and research study.

Water quality and water pollution studies generally employ field surveys, laboratory tests and sampling methods. Several sensors seem capable of providing necessary data. Color and false color films can frequently indicate the location and extent of effluents discharged into a water body. Color infrared has been used to detect excessive algae growth and sedimentation, which may have been due to surrounding urbanization and/or unprotected landscape (Strandberg, 1969). Thus, aerial photography provides an important data source in determining the causes and aerial distribution of such problems, so that proper preventative measures can be taken.

Such hydrological problems are important from other considerations too, (e.g., health hazards due to degradation in municipal water quality.

Two examples illustrating the impact of sound management are: (1) reduction in the frequency and magnitude of flash floods, and the resulting damages to human life and property; (2) controlling water pollution and sedimentation in streams, reservoirs and drainage systems.

Increasingly, thermal pollution has become a major problem for urban and rural areas. Thermal infrared imaging systems are particularly useful in detecting the sources and areal extent of warm-water discharges (Lindgren, 1974).

Status of Present Research

The results of research study during the past two decades has shown a tremendous increase in the ability to measure certain hydrologic parameters from remote sensing platforms (aircraft and spacecraft). Different spectral regions (infrared, multispectral and microwave) are being investigated for measurements concerning the dynamics of the environment. These experimental measurements are then evaluated in terms of their effects on the hydrology of the region.

Such consideration necessitates the collection of large amounts of information rapidly over large areas. Thus, new innovations are needed in data collection, data reduction and data analysis tehcniques. Moveover, such operations must be automated from the cost point of view (Skibitzke, 1976).

The Advantages of Remote Sensing

1. It provides comprehensive and rapid information which are reliable, accurate and current for large areas. Perhaps it is the only data source suitable in the survey of inaccessible areas.

2. The data is flexible as a data acquisition and analysis technique for several land use surveys. Thus, it can be designed to meet several objectives at different planning levels. It is a significant source of information in the preparation of land and water resources management plan.

3. The methods are effective in developing a data base for the geographic region.

4. It is cost effective.

To summarize, remote sensing offers alternatives and supplements present methods of data sources and data analysis. Conventional data gathering and analysis techniques are not very efficient and cost-effective in several applications and outdated for some others. Often there is a shortage of funds and manpower. Therefore, remote sensing appears to be the only alternative. Though field surveys are essential in several projects, the total task will be very much simplified.

In hydrologic studies, remote sensing provides the dynamic hydrologic data (e.g., repetitive coverage of Landsat satellites). This is essential and important since several projects in applied hydrology need current data, and the traditional data collection program (based on statistical analysis) become no longer pertinent (Skibitzke, 1976). More detailed discussions of the application of remote sensing to such hydrological problems as in flood studies and hydrologic modelling have been described in later chapters.

Hydrologic Cycle and Hydrologic Processes

Hydrology is the study of the origin, distribution and properties of the waters of the Earth (Linsley, 1958). The main elements of the hydrologic cycle: precipitation, interception, infiltration, evapotranspiration, runoff and ground water flow are controlled by processes which are complex in nature, Figure 2.

The hydrologic processes are highly variable and even erratic at times. The hydrologist needs both the qualitative and quantitative information of water in transit in the hydrological cycle and the inter-relations between them. Due to the complex inter-relations of the hydrologic phenomenon it is difficult to explain the many processes through simple deductive reasoning. Such hydrologic predictions as infiltration and evaporation rates, runoff volumes, and ground water storage are based on long term measurements of the hydrologic elements. Often decisions on planning of major hydrologic projects

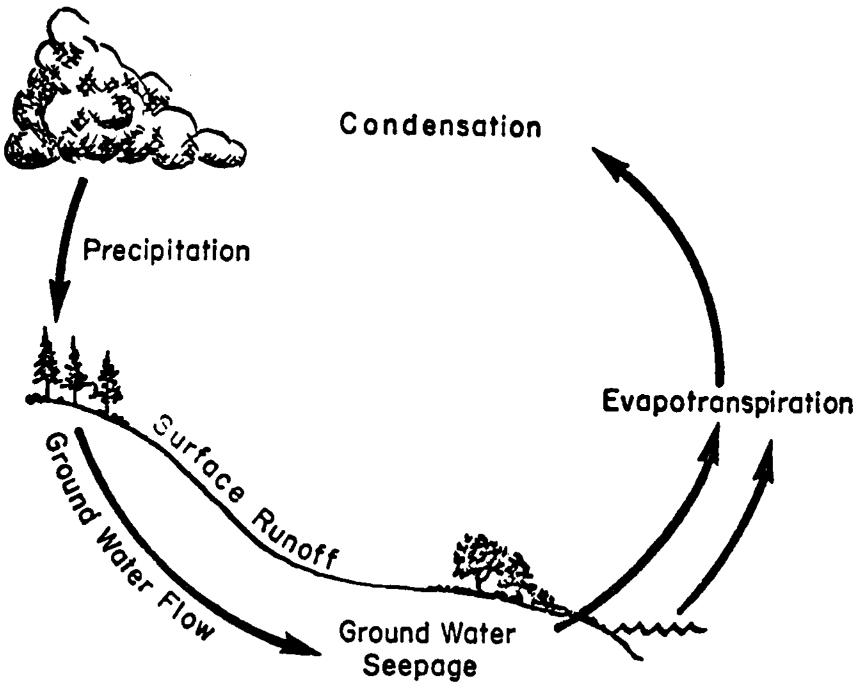


FIGURE 2. THE HYDROLOGIC CYCLE.

Source: R. Linsley, M. Kohler and J. Paulhus, "Hydrology for Engineers"; McGraw-Hill Book Company, 1958.

are based on the analysis of these hydrologic data.

In the United States, agencies like the United States Geological Survey (USGS) and the United States Weather Bureau (USWB), are noramlly responsible for the collection and the reduction of the watershed hydrologic data. From an analysis of these data, hydrologists attempt to establish relationships governing the hydrologic events. But the lack of sufficient historical data base (rainfall-runoff data) severely limits several studies.

These considerations necessitate the development of new techniques and methods, particularly for ungaged watersheds. Reliable estimates of the runoff volume and rates of runoff from watersheds are difficult for ungaged watersheds (Blanchard, 1975). Much of the hydrologic research has been directed at understanding the processes involved within a gaged watershed and later extending this knowledge to ungaged watersheds. Here, remote sensing serves as an alternative and finds wide hydrologic applications--several of the hydrologic parameters needed in quantitative analysis can be derived from remotely sensed data.

Brief Discussion of the Hydrologic Processes with Reference to Hydrology of a Watershed

Precipitation. This is a very variable factor and influenced by such factors as the geographic location, meteorology, temporal factors and orographic effects. Precipitation in all forms results when large masses of air steadily cool down below the dew point, causing condensation. It is measured by rain gages and snow gages. The rainfall factors important in hydrologic analysis are: rain depth, duration and intensity, variation of storm rainfall with time, and the distribution and location of the rain gages.

Generally, for small watersheds rainfall of high intensity but short duration (e.g., thunderstorms) cause more flood problems (e.g., flash floods) than steady rain of longer duration.

Interception. It is that part of the total precipitation (moisture) that is intercepted and stored on leaves and stems of the vegetative cover (Chow, 1964). Appreciable interception can occur depending on the type, density and areal extent of the vegetative cover. Intercepted rainfall is redistributed as throughfall, stemflow, and evaporation from the vegetation. For small storms, the vegetative cover over the stream may result in reduced channel runoff, while in major storms, this factor is negligible compared to the total precipitation.

Infiltration and Percolation. The infiltration process is concerned with the movement of water into the soil, while percolation refers to its advance through the soil. Infiltration is explained by two theories. In the first, it is considered as a surface phenomenon, entirely governed by the surface conditions, predominantly by the non-capillary porosity of the soil surface. In the second, infiltration is used to describe the movement of water into the soil as governed by the permeability of the entire profile (Chow, 1964).

Infiltration Process. Water infiltrates into an unsaturated soil in response to capillary and gravity potentials. If water is ponded on the surface, the pressure head is an additional potential causing infiltration. The capillary potential predominates initially, but as water percolates deeper and the soil water content increases, it is progressively less important. As saturation approaches, gravitational forces predominate.

The infiltration rate is the rate at which water penetrates the ground surface at any time, under the combined forces of capillarity, viscosity and gravity. Infiltration capacity is the maximum rate at which water can enter a soil. Typical infiltration capacity curves are shown for an initally dry sand and clay in Figure 3. Zero on the time scale corresponds to the beginning of a storm. Assuming that rainfall rate exceeds the infiltration capacity for a while, no recovery of an earlier capacity occurs through drainage into deeper soils. It is seen that infiltration capacity decreases as the soil

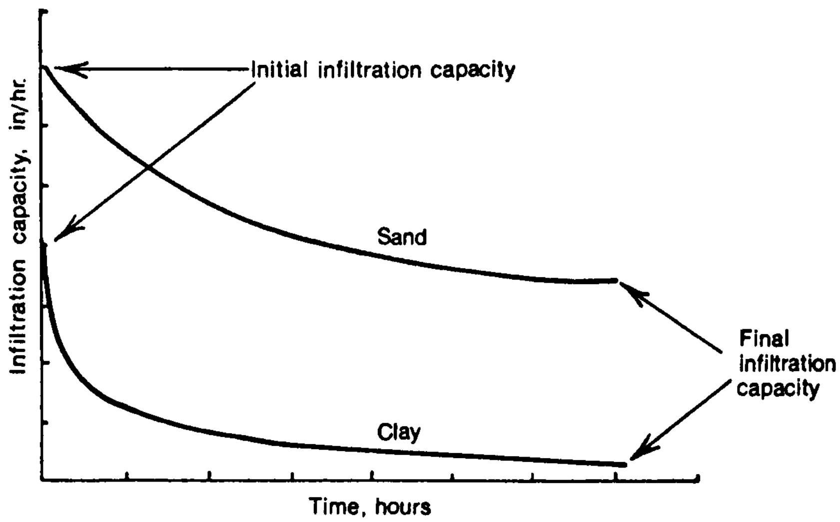


FIGURE 3. INFILTRATION-CAPACITY CURVES.

Source: J. Hewlett and W. Nutter; "An Outline of Forest Hydrology"; University of Georgia Press; Athens, 1969.

water (moisture) content increases, until a final infiltration rate is reached. If rainfall ceases or falls below the infiltration capacity, some recovery of the initial capacity will occur. Hence, the actual rate of infiltration varies, depending on how much drainage time occurs between bursts of rain. The curves illustrated in Figure 4, show the typical effects of differences in soil type and in initial soil wetness or infiltration capacity (f_i). Under the conditions indicated, surface runoff occurs only when the rainfall rate equals or exceeds the infiltration capacity (f_i). In such cases the excess water first fills the surface depressions and then flows over the land towards a stream channel. The infiltration process is important in explaining the phenomenon of surface runoff.

The infiltration theory of surface runoff is based on two fundamental concepts (Horton, 1945):

1. Infiltration capacity, which as already explained, is the maximum limiting rate at which the soil in a given condition can absorb rain as it falls.

2. When runoff occurs from any soil surface, there is a definite functional relation between the depth of surface detention, and the rate of surface runoff or channel inflow.

Infiltration capacity of a given area varies with time for a certain rainfall. Starting with an

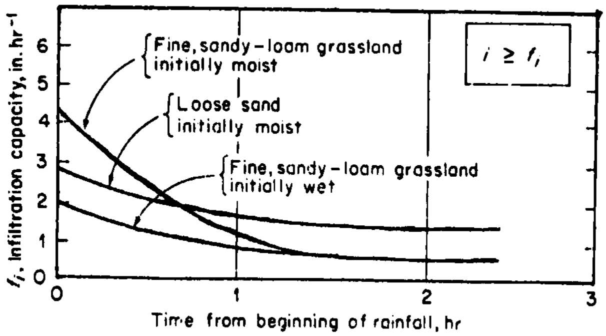


FIGURE 4. TYPICAL INFILTRATION-CAPACITY CURVES.

Source: S. Butler, "Engineering Hydrology"; Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1957.

initial value (f_o), it decreases rapidly initially, then after a certain time lapse (one half hour to two or three hours) attains a constant value (f_c). The relation between infiltration capacity and rain duration can be expressed by the following equation:

$$f = f_c + (f_o - f_c)e^{-K_f t}$$

(f, f_o, and f_c expressed in inches per hours),

where:

e = base of Naperian logarithms

t = time from beginning of rain (hours)

K_f = proportionality factor.

Infiltration capacity is governed by physical laws and processes. For any terrain it is governed by soil texture and structure, vegetative cover, biologic structures in the soil (especially at or near the surface), soil moisture content and the condition of the soil surface.

Temperature is probably also a factor, although its effect is often masked by biologic factors, which also vary with temperature and season.

These concepts of infiltration are important in understanding the processes of surface runoff and erosion. Low infiltration capacities which predominate during most of the long or heavy rains are chiefly effective in floods and sheet erosion. It is highest and least variable for pure coarse sands as compared to heavy clay soils which have the lowest infiltration capacities and saturate in a short period. Reliable estimates of the infiltration capacities, and analysis and classification of such other data, will form as important research data for a quantitative study of watershed morphology.

Factors Influencing Infiltration and Subsequent Watershed Hydrology

Soil Texture and Structure. Soils of coarse structure or well-aggregated have good infiltration capacities. In comparison, bare clay soils swell and form a dense water-proof layer that reduces infiltration. In this situation, the effect of texture is jointly correlated with soil moisture content.

Soil Moisture Content. This depends on the properties of the soil and the precipitation conditions before a storm, (i.e., antecedent soil moisture conditions).

Compaction. A major factor influencing infiltration is the degree the surface soil is compacted, which determines the soil total porosity, which in turn controls the noncapillary porosity.

Frost. Where frost is discontinuous, as in the honeycomb and stalactile types, a soil may be as permeable as or even more permeable than frost-free soil. Concrete frost, on the other hand, is almost impermeable.

Land Use and Vegetative Cover. Infiltration is practically zero in highly impervious urban areas, and is at a maximum for certain undisturbed soils under a dense forest canopy and floor. The forest floor absorbs the impact of rainfall, permitting only clean water to penetrate into the mineral soil layers.

Direct Runoff. The direct runoff refers to the various processes which ultimately produce streamflow. Its various components are channel runoff, surface runoff, subsurface flow, and base flow. In flood hydrology it is customary to deal separately with base flow and to combine all other types into direct runoff, which vary in unknown proportions.

Channel runoff occurs when rain falls on a flowing stream or on the impervious surfaces of a streamflow measuring installation. It appears in the hydrograph at the start of the storm and continues throughout it, varying with the rainfall intensity. Normally it is a negligible quantity in flood hydrographs, and is critical only in special studies.

Surface runoff (overland flow) is that part of the precipitation which fails to infiltrate into the soil and flows over the land surface as a sheet flow to the nearest stream channel. It occurs only when the rainfall rate is greater than the infiltration rate. It appears in the hydrograph after the initial demands of interception, infiltration and surface storage have been satisfied, and varies during the storm and ends during or some time after it. In general, surface runoff is governed by the following considerations (Avery, 1968).

1. Rainfall intensity and duration.

2. Antecedent soil moisture conditions.

3. Soil properties: structure and texture, drainage, permeability, etc.

4. Land use and vegetative cover.

5. Topography: Steeper slopes result in greater surface runoff.

Subsurface Flow. Subsurface flow (interflow) occurs when infiltrated rainfall confronts an underground zone of low transmission, travels above the zone to the soil surface downhill, and appears as a seep or spring. The exact part the subsurface processes and phenomenon play in the runoff process is not well understood. It is often referred to as "quick return flow" because it appears in the hydrograph during or soon after the storm.

Baseflow (groundwater outflow) occurs when there is a steady flow from natural storage-lakes or swamps, or from an acquifer replenished by infiltrated rainfall or surface runoff, or from "bank storage", which is supplied by infiltration into channel banks as the stream water level rises and which drains back into the stream as the water level falls. Baseflow does not often appear soon enough after a storm to have a significant influence on the rates of the hydrograph, but baseflow from a previous storm will increase the rates. Baseflow must be taken into account in the design of the principal spillway of a floodwater-retarding structure (Mockus, (1964).

Evapotranspiration. Evapotranspiration is that part of precipitation that is returned to the atmosphere. It consists of transpiration, the movement of water through the plant to the atmosphere, and evaporation, the movement of water vapour from the water, soil and vegetative surfaces. The proportion of moisture transpired or evaporated depends in part on the distribution of rainfall. Vegetation reduces direct evaporation from soil or snow cover. However, the high rate of absorption of soil moisture by plant roots, together with the losses due to interception, usually more than offset the effects of vegetation in retarding evaporation from the soil.

Thus, the soil in forest openings tends to have more moisture than soil beneath the trees (Chow, 1964).

The brief discussion of the hydrologic processes indicate the complexity of the watershed hydrology. The interactions between them and the inter-relations between the several watershed characteristics both in time and geographic region, are influenced by such factors as local climatic patterns and watershed characteristics (topography, soil, land use and vegetative cover, etc.).

Forest Hydrology

Forested areas are a significant contributor for usable water. Factors which contribute to this end are:

1. The large, active, surface canopy area and subsurface root system of the forests.

2. The forest litter.

3. Stability of surface soil characteristics under forests for long periods.

Hydrologically, these factors are important in processes of interception, infiltration and evapotranspiration. Since forest soils maintain high infiltration rates, forest land is a major source of high quality ground water. Surface runoff occurs depending on the degree to which forest floors have been disturbed, since infiltration capacities decrease gradually depending on the extent and manner the forest floor was disturbed. Several studies have confirmed this. In a dense cover, the forest floor consists of a humus--an organic layer immediately below the litter layer from which it is derived. Under good management practices (proper care, protection and improvement), humus is porous, having high infiltration and storage capacities. Under poor management practices (burning, overcutting, or overgrazing), humus is compact enough to impede the absorption of water (Mockus, 1964).

Further, forest-soil-water systems operate in an energy balance state. Moisture movements are governed by the physical and chemical conditions of the system. Thus, storage and transport of water in soil is related to the physical and chemical properties of both soil and water.

CHAPTER II

FLOOD STUDIES

This is a major environmental hazard caused both due to natural phenomena and also due to Man's activities on the land surface. Flood studies generally include determining the factors causing floods, their magnitude and frequency of occurrence in any area, and methods of controlling their disastrous impact--loss of life, property damage, economic loss, etc.

A flood is basically defined as a flow that overtops the natural or artificial banks of a stream. In a hydrological analysis the term flood is generally used to denote a discharge wave characterized by a certain peak discharge and, eventually, this peak discharges itself (Klemes, 1973).

Often, the runoff from small watersheds is the main water supply for several communities, and its control is important for agricultural and small town property owners. Flood control is accomplished by such hydraulic structures as dams, flood detention structures, levees, detention ponds, etc. The disastrous effects of floods are minimized by implementing the regional flood control ordinances and sound flood-plain management. Hence, there is a need for reliable estimates of flood flows for present watershed conditions, and also for conditions under future (projected) developments. This assists in the planning of watershed flood projects by avoiding expensive overdesign or disastrous underdesign of flood control structures. Overdesign can also reduce water quality by inhibiting the necessary "flushing" action (Blanchard, 1975).

Causes and Conditions of Flooding

Figure 5 depicts the complex schematic network that can contribute to flooding (Ward, 1978). Broadly, they are due to regional climatological variations (e.g., excessively heavy rainfall, snow and ice melt) and the watershed characteristics. In particular, the changes in watershed (induced due to watershed developments) are a major cause of floods in many areas.

The flood intensifying conditions cause a speed up of the movement of water within the catchment, i.e., to reduce the time of concentration. The time of concentration is the shortest time required for water falling on the most remote part of the watershed to contribute to streamflow at its outlet. Watershed lag is a measure of the weighted time of concentration and is related to the physical properties of a watershed such as area, length, and slope. The flood intensifying conditions can be grouped into watershed, network and channel characteristics. Each group has some comparatively stable

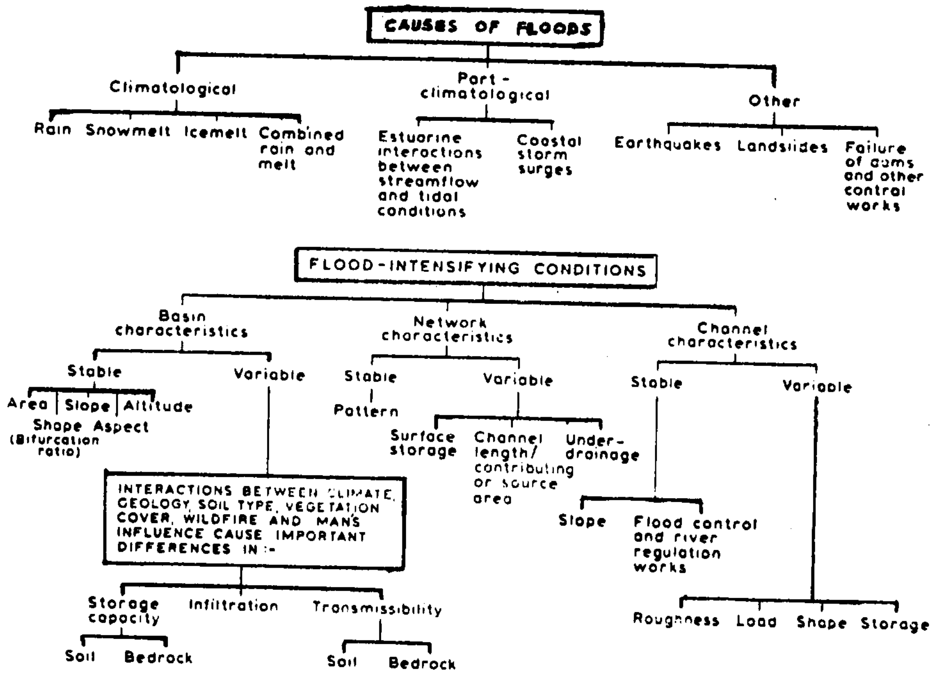


FIGURE 5. CAUSES OF FLOODS AND FLOOD INTENSIFYING CONDITIONS.

Source: R. Ward, "Floods: A Geographical Perspective"; John Wiley & Sons, New York, 1978.

characteristics while others are more variable. The effects of the characteristics are numerous and complex on flood hydrology.

Features of Flood

Stage or water depth is a common index of flood magnitude. It can be measured directly and is of immediate relevance if flood-retaining structures are likely to be overtopped.

Discharge rate is essential in predicting flood magnitude. It is estimated indirectly from measurement of "stage," utilizing a stage-discharge rating curve, as shown in Figure 6.

The term "peak rates of discharge" or "peak stage," time Y in Figure 6, is of particular interest, since it is an indication of the time of greatest danger and maximum inundation.

The flood magnitude varies with time. This determines the shape of the flood hydrograph, and the discharge volume, which is the total quantity of water measured on the flood hydrograph in time period X_1Z_1. It is a significant factor in the optimum design and operation of flood control and multipurpose reservoirs (Chow, 1956). The flood magnitude determines the depth and area of inundation and to a large extent the duration of flood, time (T_3). Also, the stage and discharge are related to the velocity of floodwaters, which is difficult

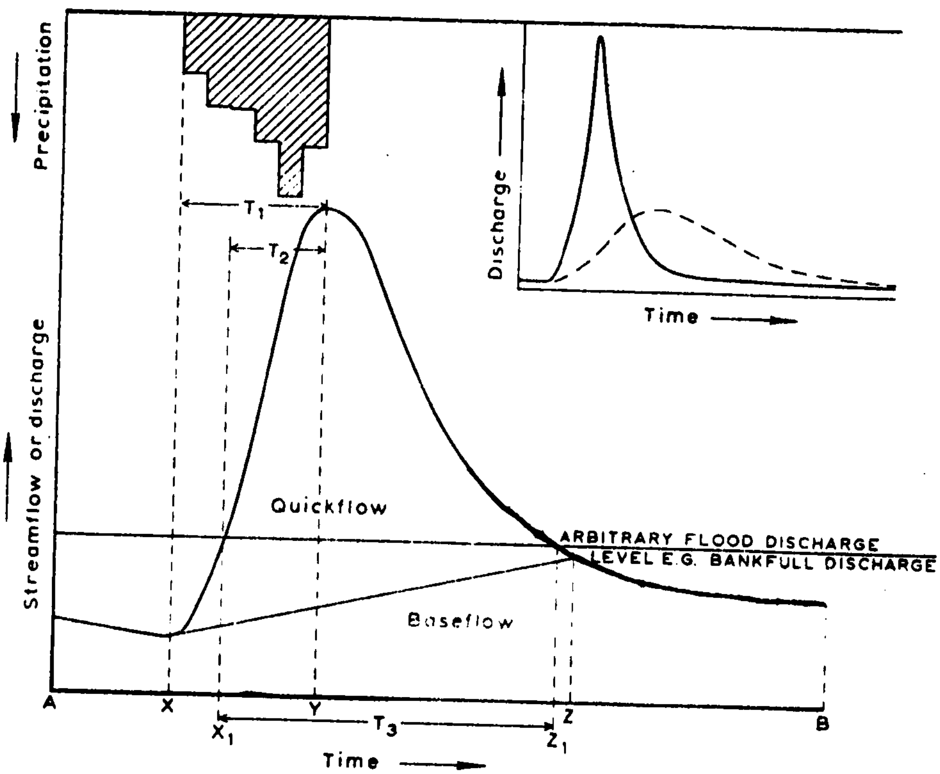


FIGURE 6. FLOOD HYDROGRAPH.

Source: Hoyt and Langbein; "Floods"; Princeton University Press; Princeton; 1955.

to measure. One promising approach, based on remote sensing, is the use of aerial photography to record the movement of special floats dropped at intervals into the floodwaters (Popov and Gavrin, 1970).

The potential flood damage of a given event is largely determined by the three characteristics of floods: depth and area of inundation, flood duration, and velocity of floodwaters.

Seasonality of flooding is another important measurable characteristic. Although large streams may show marked seasonal characteristics, on smaller streams the most severe flooding may be associated with intense convectional storms in summer. Seasonal occurrence of floods has a main bearing on the land use of floodplains.

Flood frequency is a statistical measure of the probable occurrence of a flood of a given magnitude, which aids the hydrologist and engineer in the design of flood detention structures.

The Flood Hydrograph

A flood hydrograph is a continuous trace of discharge or water depth against time during a flood event. Hydrographs, or some elements of them (e.g., peak rates) are used in the planning and design of water control structures, and also to show the hydrologic effects of existing or proposed watershed projects. The rainfall and runoff (streamflow) measurements are made at different sections and lengths along a channel. A complete hydrograph can then be constructed by established analytical methods. The shape and magnitude of the flood hydrograph depends on the climatological factors and other watershed characteristics (flood intensifying conditions). Moreover, in a large watershed, the contributing factors have to be analyzed for each sub-basin; the response of all such sub-basins are then integrated to generate the final hydrograph at the outlet.

A brief discussion of some of the common features of a flood hydrograph, due to climatological events, is as follows: Figure 6 illustrates the hydrograph of a river flood. During the dry period (AX), streamflow decreases exponentially, and the discharge is primarily due to baseflow, which is largely sustained by: (1) unsaturated interflow in small, steep, impervious catchments, (2) groundwater flow in flat, permeable catchments, or (3) by a combination of both of the above in intermediate catchments.

Rainfall begins at time X and the rapid increase of discharge between X and Y results from the generation of quickflow from the expanding channel-network contributing areas which are fed by infiltrating precipitation from above, and by interflow from below. The hydrograph peak occurs at time Y, shortly after the cessation of rainfall, and thereafter discharge is largely determined by the amount of water held in storage both on and under the surface of the catchment. The rate of exhaustion of storage is reflected in the shape of the recession limb of the hydrograph, section YB. The early part of the recession is sustained largely by saturated interflow, while the latter stages, sections ZB and AX, are sustained by the combination of unsaturated interflow and groundwater flow, depending on catchment conditions.

From the general nature of the flood hydrograph, it is seen that the discharge hydrograph is dominated by the quickflow component, with a time base XZ, and a peak Y. But, generally, flood conditions do not begin immediately as discharge increases at time X, since the initial discharge increase has not topped the channel arbitrary flood level. Hence, the actual flooding condition is considered to begin and end when this preselected discharge is equalled on both the rising and falling limbs of the hydrograph. Thus, although still peaking at Y, it will have a shorter defined time base X_1Z_1.

The general form of the flood hydrograph is greatly modified by the variation in the climatological factors (rainfall intensity, rate of snowmelt, etc.) and the several potential flood intensifying conditions, Figure 5. Thus, it may have the low peak and long time base of a sluggish stream or a high peak and short time base of a flashy stream, inset Figure 6. Present-day difficulties with hydrograph development are due to precise estimations of runoff from rainfall and distinguish between runoff and other components, particularly base flow.

Factors influencing the magnitude of the flood peak are: (1) climate, (2) watershed area, shape, elevation, slope, (3) the drainage network, and (4) vegetation and land use.

The runoff volume and discharge rates for both gaged and ungaged watersheds are estimated by empirical equations and hydrologic simulation models. The empirical equations are derived from a statistical analysis of historical rainfall runoff data for several watersheds in a particular region. They relate the climatic factors and the watershed physiographic descriptors (independent variables) and the runoff volumes and discharge rates (dependent variables). Many of the estimations based on such equations have large errors of estimates. Watershed hydrologic models are based on a mathematical approach and make predictions (estimations) of certain factors depending on a set of input parameters, (e.g., prediction of streamflows or water quality under different watershed conditions). Numerous models exist for specific applications. The reliability of any particular model depends, among other things on the accuracy of the input parameters. Some of the empirical equations widely used in the United States are listed below.

The Unit Hydrograph Method

This method is based on physical factors and theoretical concepts. Both, natural hydrographs (from recorded rainfall data) and synthetic hydrographs (for an ungaged watershed) can be generated.

The Rational Method

This is employed for computing peak discharge for small watersheds (area < 50 sq. km) and needs such input information as drainage area, rainfall intensity and duration, and watershed runoff coefficient.

The Soil Conservation Service (SCS) Curve Number System

Estimates runoff volume from rainfall data and watershed soil-cover complex.

Flood-Frequency Equations

These are derived from a statistical analysis of the historical rainfall-runoff data and the watershed characteristics. Since these factors exhibit wide variations and due to the complex nature of the interactions of the watershed characteristics, such equations are based on statistical probability theory.

Flood studies were a prominent part of a program of international cooperation in hydrology--International Hydrological Decade (IHD), sponsored by UNESCO during the years 1965-74. The outcome of such programs has been in the form of several publications on flood-flow computation (e.g., flood-flow computation by Sokolov, Rantz and Roche, 1976). It concisely describes the step-by-step procedure of flood computation in different parts of the world. But most of the computations require adequate rainfall, rainfall-runoff data and accurate estimates of the parameters involved. Current methods of data gathering and parameter estimations are expensive and time consuming. Alternative procedures are under research investigation. In this context the application of remote sensing techniques has wide potential, particularly in hydrological modelling. Difficulties are encountered in quantifying some of the factors, such as vegetation and land use, while in many cases measurements of others are simply not available (e.g., infiltration rates and rainfall intensity). Often the parameters have to be derived from map analysis and aerial photographs (remote sensing). This emphasizes the importance of quantitative geomorphology to this branch of hydrology. Quantitative parameters can be evaluated from remotely sensed data to the degree of accuracy required for the models. Further research in this area could result in better and more reliable models based on parameters amenable by remote sensing.

Urban Hydrology

Since the past few years urban hydrology is of serious concern to hydrologists and design engineers. Several studies were made to study the effects of urbanization on flood potential of small watersheds (Anderson, 1970, Espey 1974, Sauer, 1974, Olin and Bingham, 1977). These were important in the regional estimation of the increase in flood magnitude of different frequencies due to a certain urbanized condition in the watershed. In the past such projects were limited due to the non-availability of urban hydrologic data. New methods in data collection and data analysis have enabled preliminary flood frequency analysis resulting in empirical flood frequency equations. Urban hydrology is complicated by the trend in the urban growth characteristics of a watershed. Research in the development and application or urban hydrologic models is also ongoing (e.g., EPA Storm Water Management Model). Many of the models are complex and several of the input parameters are not well defined. This imposes limitations in their applications and the models have to be simplified, wherein the parameters can be easily estimated by such means as available urban data, maps, field surveys, etc. Here again, remote sensing finds appropriate application using aerial and satellite data. The necessary land use information and hydrologic parameters can be estimated to the required accuracy needed in several models used in urban hydrology.

Some General Conclusions of the Urban Flood Frequency Studies

1. Urbanization significantly increases the peak discharges of floods.

2. The increase in peak discharge is generally less significant with increasing flood frequencies, (i.e., the increase is more significant for the two year and five year floods than for the less probable fifty year and one hundred year floods). A conclusion is that the effects of urbanization is more pronounced for the more frequent (two year and five year) floods.

3. On small steep catchments, the drainage improvements alone may triple average flood magnitudes, and complete development of the stream channels with a 100 percent impervious cover may increase average floods by a factor of nearly eight (Anderson, 1970).

4. Two main factors affecting urban hydrology are: (1) percent of impervious area, and (2) percent of area under storm sewers.

Percent of imperviousness is that part of the watershed that is covered by concrete pavements, roads, rooftops, etc. It is an indication of the proportion of the drainage area from which surface runoff contributes directly to increased runoff rates in downstream areas. It increases direct runoff by reducing infiltration and depression storage. The runoff volume is governed primarily by infiltration characteristics, and is related to landslope, soil type and vegetative cover.

The percent of area in storm sewers is an arbitrary measure of the extent to which the area is served by storm sewers (gutters, storm drains, etc.) and improved channels. This factor does not appreciably affect the runoff volume, but results in reduced "lag" time (i.e., storm runoff is drained much faster). As a result flooding increases in intensity (peak rates of discharge) and frequency.

The effect of urbanization on the runoff is shown in a flood hydrograph in Figure 7. Watershed lag is decreased, resulting in increased peak discharges, which is also influenced by shorter man-made channels. The net result is that floods increase in number and intensity, while the base flow of a stream is decreased.

The flood frequency equations and hydrologic models provide predictive tools for describing the flood frequency characteristics of an urban watershed as a function of climatic, physiographic and urban factors. But they are limited in their accuracy and application, and hence should be verified by other methods. But as additional urban data (sewer areas, area covered by

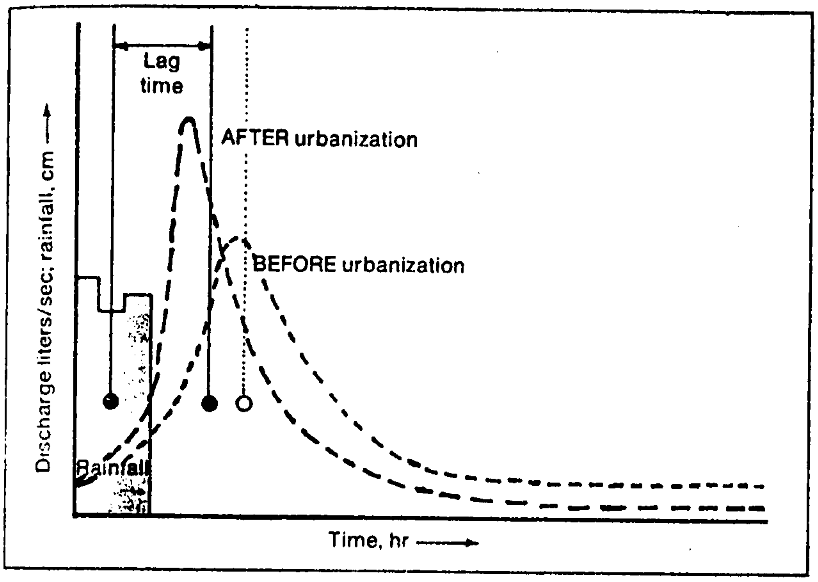


FIGURE 7. HYDROGRAPH SHOWING VARIATIONS IN STREAMFLOW WITH TIME IN AN URBAN AREA.

Source: W. Hamblin; "The Earth's Dynamic Systems"; Burgess Publishing Company; Minneapolis, Minnesota; 1975.

roads, etc.) are collected, the equations can be tested and calibrated again, based on more hydrologic data and climatic factors.

Urbanization in all forms affects water quality. The principal effect of land use on sediment is due to the exposure of soil to storm runoff (Leopold, 1968). An example of the watershed water quality study is the "County 208 Program", which is a regional water quality management program mandate by the Environmental Protection Agency (EPA). The study is in a sense a land use planning regulation, wherein the runoff and non-point source pollution are estimated under different land use and land condition practices.

The SCS Curve Number System

This is an empirical equation developed by SCS about 1947 (Mockus, 1964) to estimate storm runoff volume, which can then be extended by vigorous analytical methods to predict peak discharges (e.g., unit hydrograph). It has been widely used in the hydrologic design projects (estimate flood-flows and determine required storage for flood-detention structures), and is particularly applicable for ungaged (un-instrumented) watersheds.

The storm runoff equation is expressed as:

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

$$S \geq 0$$

$$S = \frac{1000}{CN} - 10 \text{ (inches)}$$

where

Q = storm runoff (inches)

P = weighted storm rainfall (inches)
(design storm depth)

S = watershed potential maximum storage (inches)
(watershed storage factor)

CN = weighted curve number of the watershed
hydrologic soil-cover complex (dimensionless)

The coefficients (0.2) and (0.8) are arbitrarily selected from assumptions relating initial abstraction to potential infiltration, used in developing the equation. The storage factor varies without limit upwards from zero, which represents a completely impervious area. It is expressed in terms of the curve number (CN) for a more convenient numerical computation.

The dimensionless curve number varies within the limits:

$$0 < CN < 100 \qquad 0 < S < \infty$$

and equals 100 when $S = 0$ and 0 when $S = \infty$.

The curve number is an estimate of the "runoff coefficient" and depends on the soil-cover complex (i.e., the hydrologic land use cover, hydrologic soil grouping, antecedent soil moisture, etc.) at the time of investigation.

The soil types are grouped into four hydrologic soil groupings (A, B, C, and D) depending on their properties (infiltration, permeability, etc.). As already mentioned, infiltration rate is the rate at which water enters the soil, and permeability is the property which governs the mobility of water through it. These factors are influenced by the drainage class of the soil as well as its texture and thickness. Group A soils are coarse, sandy soils which drain well. Thus, they have the highest infiltration rates and the lowest runoff potential.

Group D soils, on the other hand, consist of heavy clays and are the most poorly drained. They have the lowest infiltration rates and the highest runoff potential. Groups B and C are classified appropriately in between these extremes.

The application of the storm runoff equation requires two inputs: (1) rainfall and (2) curve number. Though rainfall data are generally available, the determination of accurate curve numbers is the weak link in the system. It is presently estimated by semi-objective field surveys and referring to the SCS Engineering Tables (Mockus, 1964). Detailed methodology in the development, application and limitations of the equation under specific conditions are also described. The equation was developed to estimate runoff volume for small ungaged watersheds from data on rainfall and curve number (i.e., adequate rainfall-runoff records do not exist for estimation of curve number). The equation can be used as a "submodel" in the more complex continuous watershed models. The curve number is a variable factor, depending on the actual surface conditions.

The runoff volume (Q) was computed for different rainfall depths (P) up to 12 inches for a curve number (CN) of 40 and 43. The results are shown in Table 1 and graphically in Figure 8. Similar estimations were done for a CN = 70 and CN = 75, shown in Table 2 and Figure 9. The wide variations in (Q) in the two ranges indicates that the curve number method of estimating runoff volume has limitations and should be used with caution.

Table 3 lists the land cover pertinent to hydrologic studies and Table 4 lists the curve numbers for different hydrologic soil-cover complexes.

Application of Remote Sensing

For small watersheds, the current methods of estimating curve number (field surveys and aerial

TABLE 1

ESTIMATION OF STORM RUNOFF VOLUME (Q) CASE I

Rain Depth (P) (inches)	Runoff Volume: Q (inches) Present Condition CN = 40	Future Condition CN = 43	Percent Change in Q
1.0	0.31	0.23	25.8
1.2	0.25	0.18	28.0
1.6	0.14	0.09	35.7
2.0	0.07	0.03	57.1
2.5	0.02	0.002	90.0
3.0	0.0	0.01	-
4.0	0.06	0.12	100.0
5.0	0.24	0.35	45.8
6.0	0.50	0.68	36.0
7.0	0.84	1.07	27.4
8.0	1.25	1.54	23.2
10.0	2.23	2.62	17.5
11.0	2.76	3.23	17.0
12.0	3.38	3.87	14.5

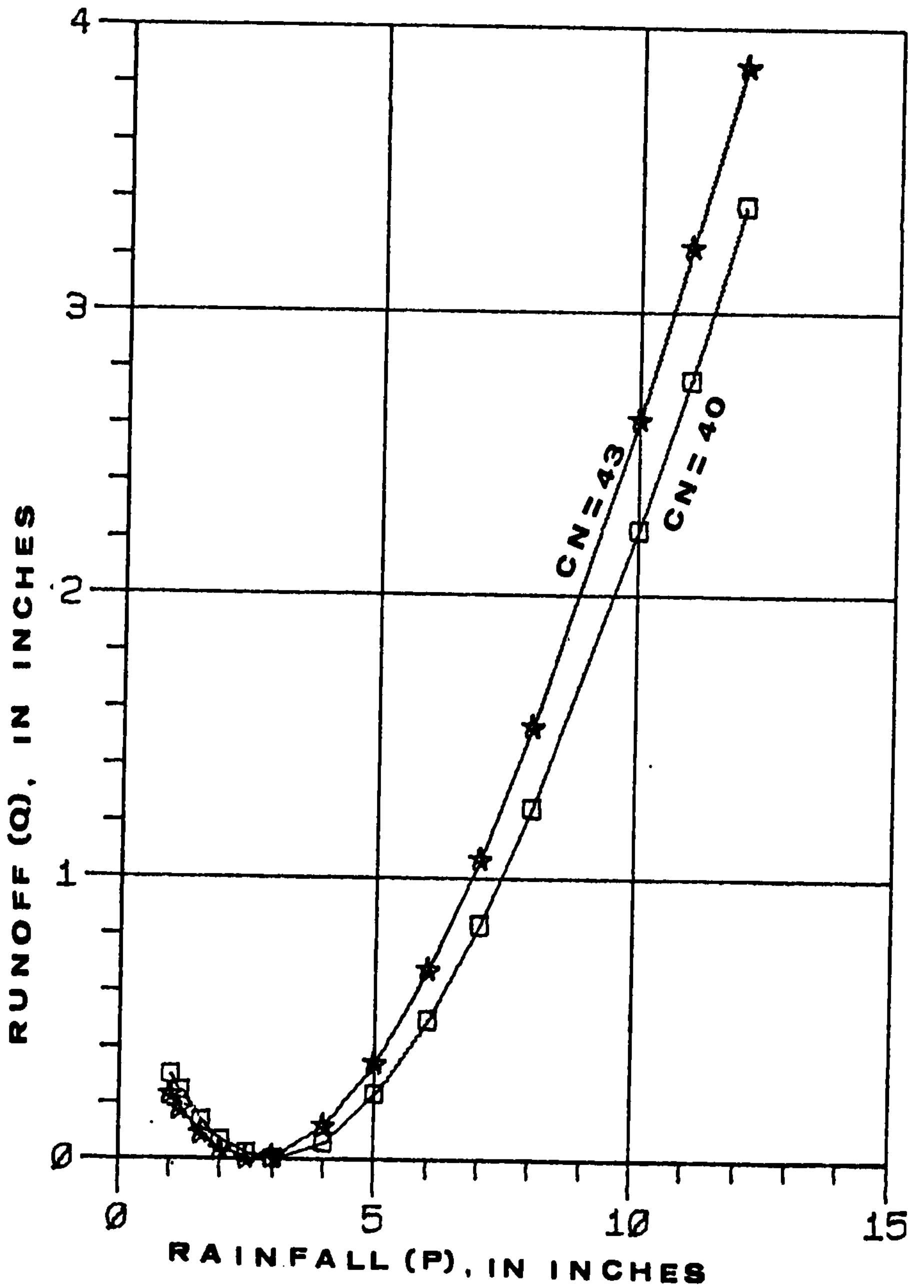


FIGURE 8. RAINFALL-RUNOFF GRAPH FOR CASE I.

TABLE 2

ESTIMATION OF STORM RUNOFF VOLUME (Q) CASE II

Rain Depth (P) (inches)	Runoff Volume: Q (inches) Present Condition CN = 75	Future Condition CN = 80	Percent Change in Q
1.0	0.03	0.08	166.7
1.2	0.13	0.24	84.6
1.6	0.29	0.44	51.7
2.0	0.38	0.56	48.0
2.5	0.65	0.89	36.9
3.0	0.96	1.25	30.2
4.0	1.67	2.04	22.2
5.0	2.45	2.89	18.0
6.0	3.28	3.78	15.2
7.0	4.15	4.69	13.0
8.0	5.04	5.62	11.5
10.0	6.88	7.52	9.3
11.0	7.82	8.48	8.4
12.0	8.76	9.45	7.9

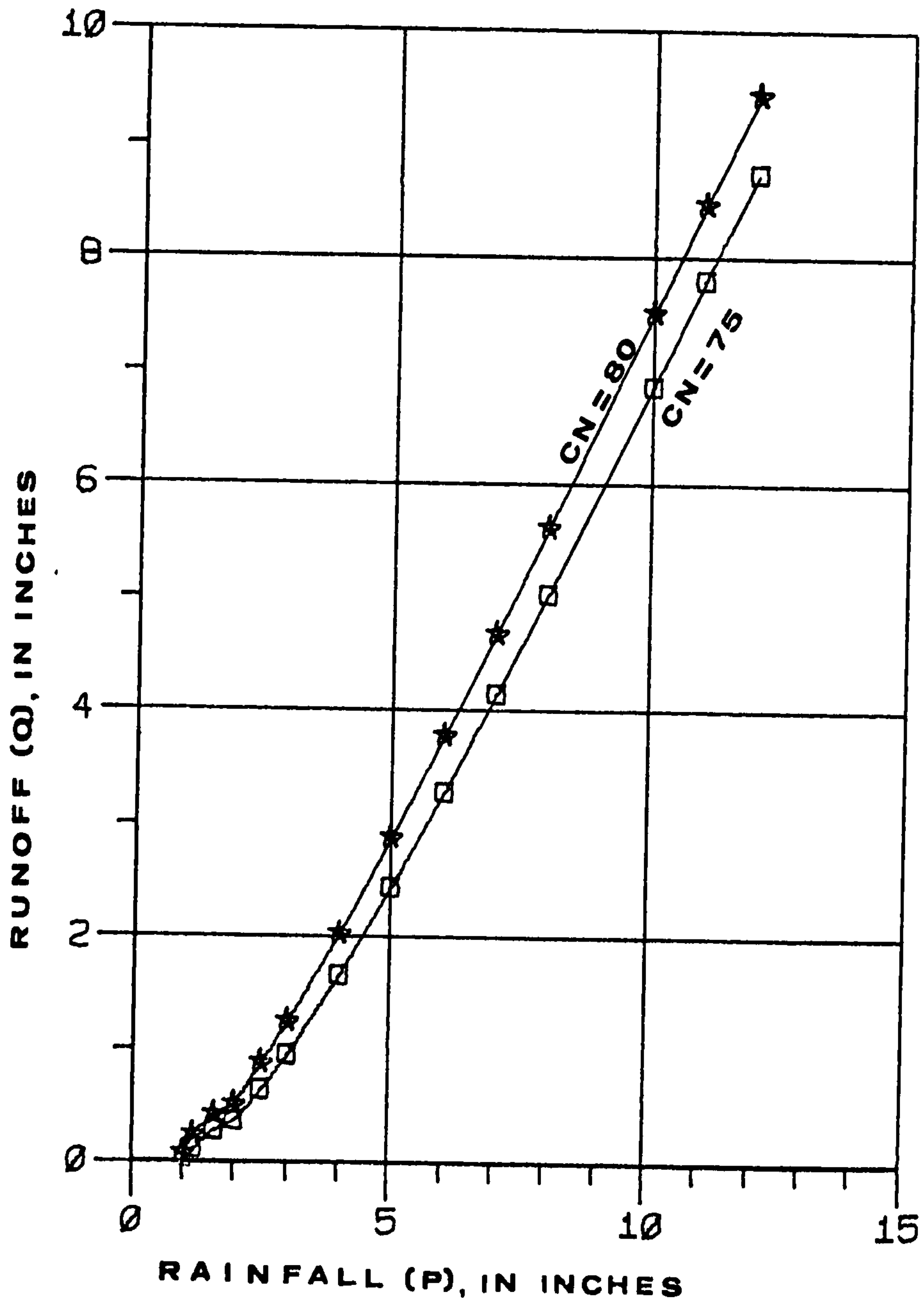


FIGURE 9. RAINFALL-RUNOFF GRAPH FOR CASE II.

TABLE 3

LAND COVERS PERTINENT TO HYDROLOGY

Land Cover	Description
Urban	"Areas of intensive use covered by structures." Hydrologically, it is important only to delineate impervious areas from pervious.
Residential	Areas of dwelling, both high and low density.
Cropland	Land used for the production of row crops; may be bare ground during certain seasons.
Pasture	Land covered in grass or grass-like crops such as close-seeded legumes, rotation meadow and rangeland. (Although Anderson groups cropland and pasture together, they were defined individually for the ground truth map since the hydrologic response may differ depending on the time of year).
Forest	"Areas having a tree-cover areal density of 10 percent or more." Forests can be broken down into deciduous and evergreen but this degree of breakdown was not necessary for this study.
Wetlands	Wet areas usually covered by vegetation, either trees (cypress, for example) or brush.
Open Water	Wet area not covered in vegetation, for example ponds, lakes, and reservoirs.

Source: J. Anderson, et al. 1976. A Land Use/ Land Cover Classification System for Use with Remote Sensor Data," Geological Survey Professional Paper No. 964.

TABLE 4

RUNOFF CURVE NUMBERS FOR SELECTED LAND USE AND LAND COVERS

Land Use Description		Hydrologic Soil Group A	B	C	E
Cultivated land[1/]:					
without conservation treatment		72	81	88	91
with conservation treatment		62	71	78	81
Pasture or range land:					
poor condition		68	79	86	89
good condition		39	61	74	80
Meadow: good condition		30	58	71	78
Wood or forest land: thin stand, poor cover, no mulch		45	66	77	83
good cover[2/]		25	55	70	77
Open spaces, lawns, parks golf courses, cemeteries, etc.					
good condition:	grass cover on 75% or more of the area	39	61	74	80
fair condition:	grass cover on 70% to 75% of the area	49	69	79	84
Commerical and business areas (85% impervious)		89	92	94	95
Industrial districts (72% impervious)		81	88	91	93
Residential[3/]:					
Average lot size	Average % impervious[4/]				
1/8 acre or less	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
Paved parking lots, roofs, driveways, etc.[5/]		98	98	98	98

TABLE 4 (continued)

Land Use Description	Hydrologic Soil Group A	B	C	E
Streets and roads:				
paved with curbs and storm sewers 5/	98	98	98	98
gravel	76	85	89	91
dirt	72	82	87	89

1/For a more detailed description of agricultural land use curve numbers refer to National Engineering Handbook, Section 4, Hydrology, Chapter 9, August 1972.

2/Good cover is protected from grazing and litter and brush cover soil.

3/Curve numbers are computed assuming the runoff from the house and driveway is directed towards the street with a minimum of roof water directed to lawns where additional infiltration could occur.

4/The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers.

5/In some warmer climates of the country a curve number of 95 may be used.

Source: "Urban Hydrology for Small Watersheds: USDA-SCS, Technical Release No. 55, 1975.

photographs) is best suited and adopted. But for large watersheds, the parameter is to be determined for each sub-basin, for meaningful hydrologic application. Thus, traditional methods become impractical. This necessitates more efficient procedures of gathering land cover and soil descriptions. Here satellite digital data provide the necessary land cover information (NASA, 1976).

Thus, remotely sensed data (aerial and satellite data) provides a reliable data source in determining two main parameters, land cover and soil data, essential in several hydrologic studies.

Depending on the resolution requirements for the study, the appropriate data is chosen for mapping. Significant watershed data should be identifiable and classified. Both manual methods (photointerpretation) and computer-aided analysis can be utilized. By the latter method and accurate ground truth, mapping can be achieved relatively accurately.

Selective underflights by aircraft can be used to support and supplement the broad data acquisition capability of synoptic satellite coverage. Classification from satellite data is based on multistage sampling using the higher resolution aerial data and ground truth information.

Thus, more research has been done to identify land cover classes than other parameters used in the watershed description. But recently, research in the area of soils (e.g., soil mapping from spectral characteristics, soil moisture estimations from microwave measurements) have been conducted with some success, but very little is known in the delineation of the hydrologic soil groups. Further research along these areas looks very promising.

CHAPTER III

METHOD OF ANALYSIS

Study Area

Two small watersheds (< 5 square miles), Fagan Creek and Aldridge Creek were chosen for this study; both located in Madison County, Alabama. The hydrologic study of both the watersheds are presently under investigation. The Aldridge Creek drains about 22 square miles. There are no gaging stations within the Fagan Creek catchement, while two streamgage stations and one rain gage operate within the Aldridge Creek watershed. Two other rain gages operated in the vicinity. The rainfall-runoff records are maintained by the United States Geological Survey (USGS) while that from the rain gage by the city fire station. Though an extensive network of gaging stations operate in the vicinity of these watersheds, at present only limited data are available.

The topography and land cover varies from east to west in the Fagan Creek: steep in the east with dense vegetation to flat to rolling in the west covering part of the Huntsville downtown area. It drains into the Huntsville Spring Branch, a major drainage system in Huntsville city. Aldridge Creek runs north-south draining into the Tennessee River. Its upstream area is steep and densely vegetated. Of specific interest in both these watersheds are the hydrologic effects of urbanization on the steep slopes and the valley floors (e.g., Aldridge Creek is experiencing runoff changes due to present developments). An ad hoc committee was set up by the Huntsville Planning Commission in April 1979 to study all aspects of future slope development. Their findings and recommendations are contained in a final report released in July 1979 (Huntsville Planning Commission, 1979). Since the hydrology of the region depends on several other physiographic factors, a brief summary of the same is outlined for Madison County. (Source: Geological Survey of Alabama, Atlas Series 8, 1975).

Topography

The county's topography is dominated by hills east of Huntsville. These uplands are the Appalachian Plateau--part of the Appalachian Mountains. The western edge of this area, the Cumberland Escarpments, joins with the Interior Low Plateaus area at its base--the latter rolling lands of western Madison County. This difference is attributed to the variation in the resistance of rocks to weathering by atmosphere and erosion by running water. Sandstone, which is more resistant to weathering and erosion, has not been removed in the Appalachian Plateau, but has been in the Interior Low Plateaus. The limestone and shale, which are protected by the sandstone in the uplands, is being weathered and eroded in the lowlands.

Most scattered hills remaining west of Cumberland Escarpment have no sandstone cap and are shortlived geologically speaking. Mountains east of Huntsville area are Monte Sano, Round Top, Garth, Huntsville and Green Mountains.

Slopes

Topographic relief varies from east to west across the county. The eastern part is characterized by hills rising more than 900 feet above the valley floors in the watersheds of Paint Rock River, Flint River, and Aldridge Creek. In contrast, the western part consists of broad, rolling hills of slight to moderate relief, generally less than 300 feet. Poor drainage conditions usually occur in such low-slope (up to 1 percent) areas, and flooding is possible adjacent to rivers and smaller streams. Areas of slopes of (1 - 10 percent) occupy a major part of the Madison County. Steep slopes, even up to 40 percent occur on the hill slopes (e.g., Mountainbrook, and Fagan Spring).

Climate

The climate is classified as humid, subtropical. Both winter and summer rains occur, but the autumn is usually dry, the mean annual precipitation being 48.7 inches. Snow, sleet or hail are rare. Winter precipitation is greater than summer and more prolonged due to cold air masses being overridden by warm, moist air masses from the Gulf of Mexico. Summer precipitation is usually casued by rising air in convection cells and rainfall is intense, but of short duration. Tornadoes have been known.

Geology

Several problems arise due to the land's geological origins. Much of the county is underlain by a calcerous bedrock formation that decomposes relatively fast under the action of ground water. Several potential areas of sinkholes, caves and springholes occur and the rock is unstable for support if it has been severely weathered.

Soils

The factors influencing the soil forming process and weathering are: topography, type of parent material, biological activity, climate and time. In Madison County, the topography and type of parent material are dominant factors influencing weathering and are responsible for a wide variety of soil types: some are highly erodible; some swell and shrink according to their water content; some are too weak to support heavy structures or traffic; some are too extremely thin to exhibit good drainage; and most have "steep phases" where grade itself is prohibitive. In several locations soil erosion and soil stability problems exist. Erosion may cause potential destruction in critical areas of Aldridge Creek, where severe flooding has been experienced. This necessitates effective erosion control practice and proper treatment of existing vegetation on developing sites.

Hydrology

The water resource is an important factor in the development of the Madison County; both surface and groundwater resources are available. Though the Tennessee River forms a major source, several channels, creeks, lakes and groundwater reservoirs exist. The distribution of the hydrologic cycle is as follows. Annual precipitation (49 inches) = evapotranspiration (28 inches) + overland flow (10 inches) + infiltration (11 inches). This indicates high rates of evaportranspiration losses, but the surface soils have appreciable storage capacities resulting in potentially available water of 21 inches (about 43 percent of the total annual precipitation). It has to be noted that significant variations occur in different localized regions due to variations in the contributing factors. Further, the effects of urbanization in the densely vegetated steep slopes of the Fagan Creek and in the upper reaches of Aldridge Creek would need special studies and constraints on further developments, and alternatives have to be established. Its effect on the hydrology of the area (flood, erosion, water quality, and sedimentation in stream channels, etc.) have to be evaluated.

Presently, the Huntsville city and vicinity have an adequate widespread and complex network of storm sewerage systems. Channels such as the Huntsville Spring Branch, Fagan Creek and Aldridge Creek have been deepened, widened, straightened and lined with concrete to carry the increased volume of runoff, due to continuing development. Storm flow collects in various channels of the drainage system, where flood-stages have been created (e.g., flood of March 1973). In certain places, groundwater appears as springs, and at certain other places is discharged into streams, contributing to base flow that sustains flow during dry weather. But careful analysis and evaluation of present hydrology and hydraulics of streams is needed in planning for future construction and drainage improvement plans. To this end, it is hoped that this study report would assist in stressing the potential application of remote sensing in different studies related to watershed planning and management.

Application of Remote Sensing

The Fagan Creek watershed was chosen for estimating the effects of urbanization on flood frequencies; and also for estimation of runoff curve numbers. An upstream sub-basin of Aldridge Creek was selected for a preliminary hydrologic modelling. The data used and the sources of the same are listed in Table 5.

TABLE 5

DATA AND DATA SOURCES

Data	Parameters Derived	Data Source
Land use Landcover	Percent of imperviousness, SCS curve number, Manning's roughness coefficient, etc.	NASA 1:24,000 Color infrared photography (Date: October, 1978)
Topography	Watershed area, channel length, channel slope, ground slope, etc.	TVA/USGS Topographic Maps, Scale 1:24,000 Huntsville, Alabama Quadrangle 1975); Supplemented by 1:4,800 topographic maps supplied by City of Huntsville Planning Office.
Soil	Soil infiltration capacity, soil moisture capacity, etc., (estimated from soil data and experimental data).	Soil Survey Report, Madison County, Alabama (Issued February 1958). Geological Survey of Alabama Atlas Series 8, 1975.

Advantages of Color Infrared Imagery

A primary reason for using color infrared imagery was because of its ready availability. Recent imagery (October 1978) was acquired from the NASA office in Huntsville, Alabama. The scale of 1:24,000 was particularly advantageous for analysis since it was compatible with the USGS/TVA topographic map.

Principle of Color Infrared (CIR) Photography Reversal Color Film

The near infrared spectral range recorded by photography extends from 0.7 micrometer (μm) to about 1.35 micrometers. But normally the region from 0.7 μm to 0.9 μm is used.

Kodak Ektachrome infrared film was designed for aerial photography and is useful for camouflage detection and remote sensing applications where infrared discrimination is required. It has a film base with "false color" reversal emulsion. False color films differ from ordinary color films in that the three layers are sensitive to green, red and infrared radiation instead of the usual blue, green, and red used for normal rendition in the visible spectrum. A yellow filter (such as Kodak Wratten Filter No. 12) is normally used over the camera lens to absorb the blue radiation to which all three layers are sensitive (Kodak, 1971).

As in any color reversal film, energy in a certain band will result in the color or dye associated with that band disappearance and the resulting color of the scene will be determined by the dyes in the unexposed or remaining bands. Therefore, when the film is processed as recommended, the green-sensitive layer is developed to a yellow positive image, the red-sensitive layer to a magenta positive image, and the infrared-sensitive layer to a cyan positive image. The colors blue, green and red appear in the final transparency, but with false rendition; the blue resulting from green exposures, green from red exposures, and red from infrared exposures as shown in Figure 10.

Further advantages of color infrared at this scale are:

1. It provides an efficient and an optimum method in determing the spatial relationships, delineating boundaries and identifying certain kinds of land use and vegetative cover, and land use activities.

2. Color infrared at medium scales provides adequate ground resolution for data extraction of several watershed characteristics. This high level of classification of surface features enables better estimates of the hydrologic parameters, which are input for several empirical equations and hydrologic models. Further, the

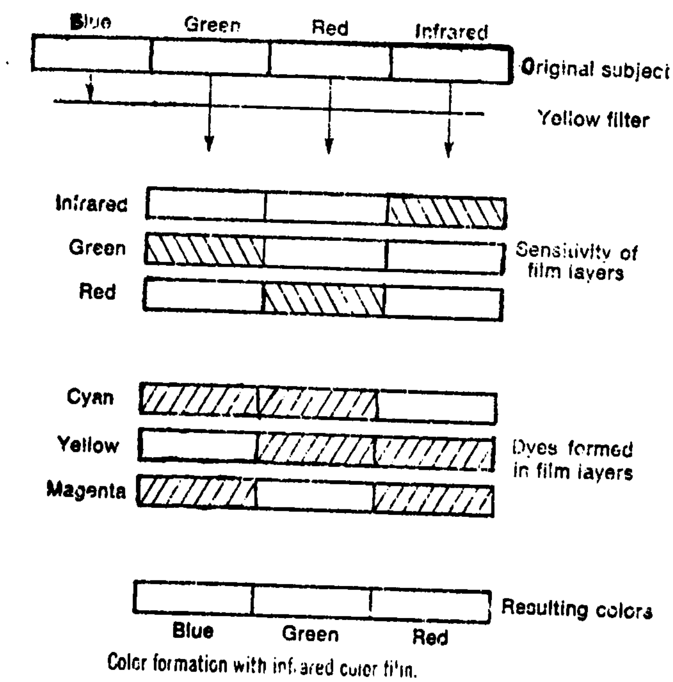


FIGURE 10. SCHEMATIC ILLUSTRATION OF POSITIVE TRANSPARENCY REVERSAL COLOR FILM PRINCIPLES.

Source: Kokak Company, "Kodak Data for Aerial Photography, M-29"; Rochester, New York, 1971.

data analysis can be done by simple photointerpretation techniques.

3. Since color infrared film has a longer wavelength sensitivity than normal color film, it has a high haze-penetration capability. This is particularly advantageous in industrialized and urbanized areas, where haze and smog create problems.

4. The other advantage is the high contrast exhibited by different surface features. Healthy vegetation which is highly reflective in the infrared, appears reddish on CIR film; cultural features having mixed reflectances appear blue, and surface water which highly absorbs infrared wavelengths appear dark. This assists in identifying several broad land use and vegetative cover classes and even delineating sharp boundaries (e.g., between vegetation and surface water).

Flood-Frequency Estimation: Fagan Creek

Empirical equations have been developed for estimating floods in small natural streams in Alabama (Olin and Bingham, 1977). The equations are shown in Table 6. The equations were developed by multiple regression analysis of flood magnitudes obtained from both observed peak discharges and synthetic discharge data generated with a calibrated rainfall runoff model and physical watershed characteristics. The analysis included data from thirty four streams in Alabama, four in Georgia

TABLE 6

FLOOD-FREQUENCY EQUATIONS AS DEVELOPED BY OLIN AND BINGHAM (1977) OF UNITED STATES GEOLOGICAL SURVEY, TUSCALOOSA, ALABAMA

	Standard Error of Estimate, Percent*
$Q_2 = 92.8\ A^{.646} S^{.237}$	43.9
$Q_5 = 166.2\ A^{.683} S^{.193}$	30.6
$Q10 = 229.8\ A^{.700} S^{.166}$	30.3
$Q25 = 332.0\ A^{.715} S^{.132}$	31.5
$Q50 = 421.7\ A^{.727} S^{.110}$	32.6
$Q100 = 532.1\ A^{.731} S^{.087}$	33.9

Q = the estimated discharge, in cubic feet per second (ft^3/s), for the indicated recurrence interval,

A = the contributing drainage area, in square miles (mi^2),

S = channel slope in feet per mile, determined from the difference in elevations at points 10 and 85 percent of the distance along the main channel from the discharge site to the drainage-basin divide. The difference in elevations is divided by the main-channel length in miles between the two points.

*All regression coefficients are statistically significant at the 5 percent level.

and three in Mississippi taken over a period of three to twenty four years. The analysis indicates that the drainage area and the main channel slope are the most significant watershed characteristics affecting flood magnitude and frequency. The equations are applicable for drainage areas up to 16 square miles and channel slopes up to 300 feet/mile. The estimations under natural conditions can be extended to urbanized conditions by methods suggested by Sauer (1974). These take into account such factors as: (1) the percent of impervious area and percent of watershed area served by storm sewers, from which an urban factor (R_L) is determined applying Leopold curves, Figure 11 (Leopold, 1968), and (2) rainfall-intensity ratio (R_t), Table 7 based on United States Weather Bureau Technical Paper No. 25. From these data the urban peak discharges are estimated for different flood recurrence intervals. But it is important to note that appropriate regional (local) values of the factors are used and all assumptions are reasonable for the study area.

Methodology

The Fagan Creek watershed and its sub-basins were delineated, Figure 12, on the USGS/TVA topographic map, Huntsville, Alabama, quandrangle, based on such factors as stream network, relief and contours. The drainage area

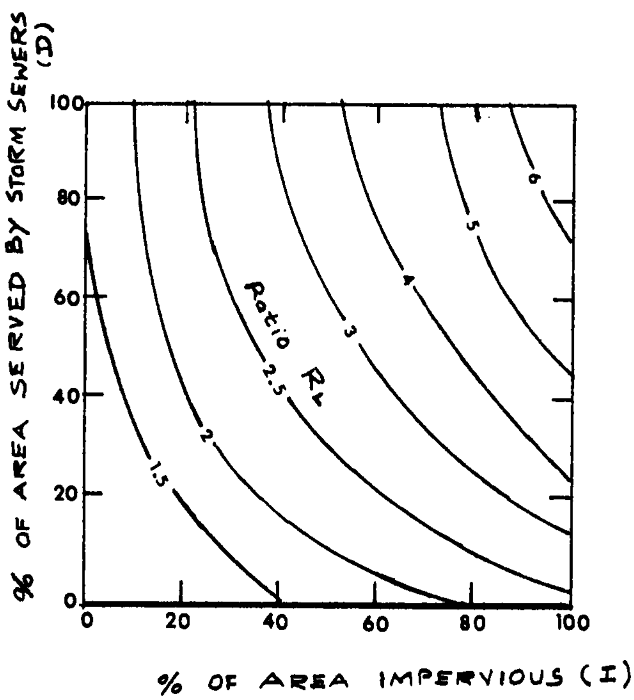


FIGURE 11. GRAPH SHOWING URBAN ADJUSTMENT RATIO (R_L) FOR MEAN ANNUAL FLOOD.

Source: L. Leopold, "Hydrology For Urban Land Planning--A Guidebook on the Hydrologic Effects on Urban Land use"; Geological Survey Circular, 1968.

TABLE 7

RAINFALL INTENSITY RATIO (R_t) FOR USE WITH FLOOD-FREQUENCY EQUATIONS

Recurrence Interval t (years)	24 Hour Rainfall Intensity ratio, (R_t)
2	1.00
5	1.3
10	1.53
25	1.82
50	2.06
100	2.24

Source: U. S. Weather Bureau Technical Paper Number 25.

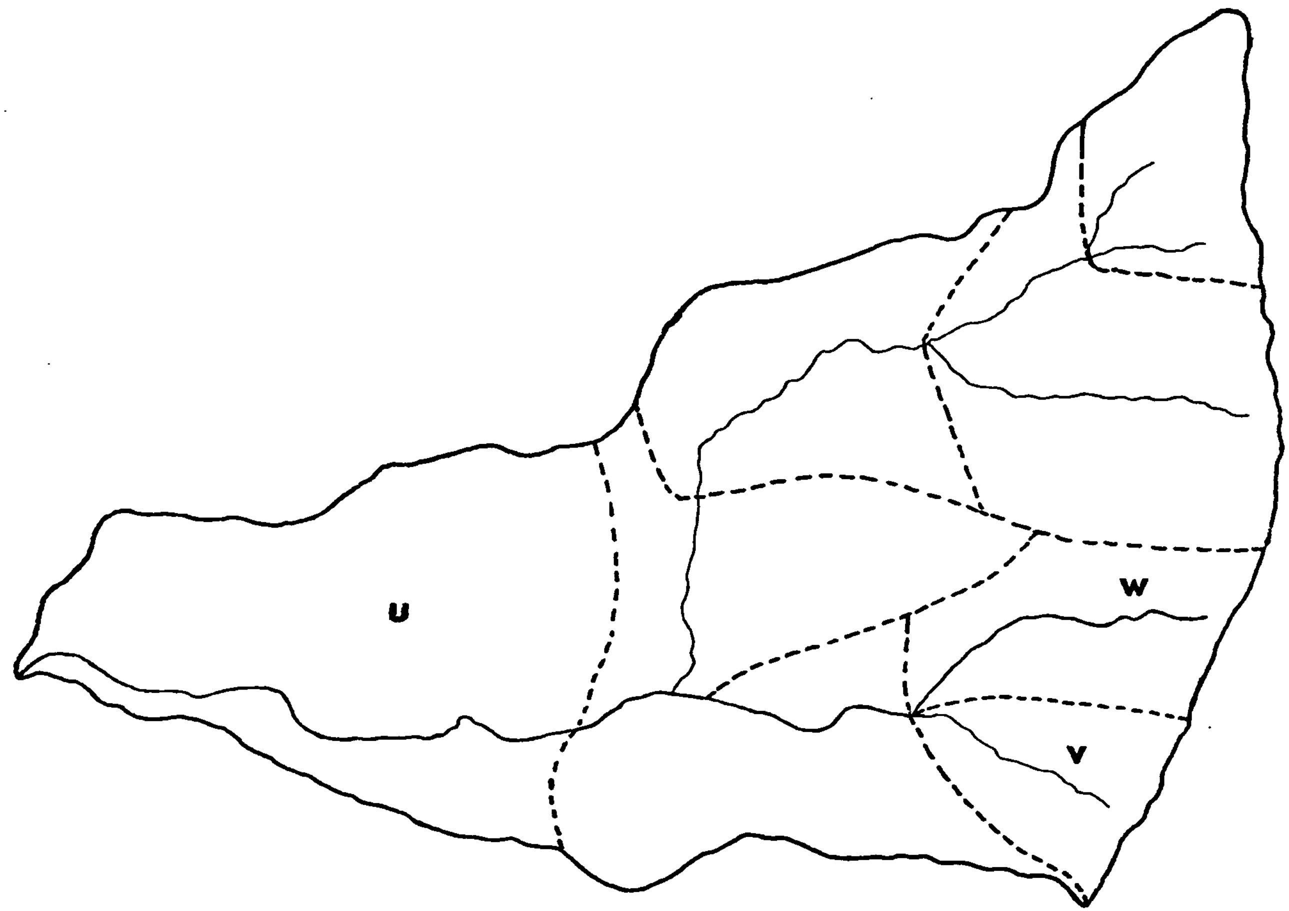


FIGURE 12. FAGAN CREEK WATERSHED WITH SUB-WATERSHEDS.

Approximate Scale: 1:105,600.

and the main channel slope were determined using an area measuring grid and an instrument device for measuring lengths on maps.

Six classes of land use and land cover were selected for classification using the color infrared imagery and simple manual photointepretation and a Zoom Transfer Scope. Using the TVA topographic map as a base map, an accurate analysis was done. Table 8 is an arbitrary empirically-derived table relating land use and percent of impervious factor (Kent, 1972). A land use, land cover map was drawn, Figure 13, and the areas under each class were measured and tabulated, Table 9. From these data a weighted percent of imperviousness (I) is determined for the watershed.

Calculations

Fagan Creek--Flood Frequency Calculation

In applying the flood frequency equations and its extension to urban conditions the following points have to be borne in mind:

1. The equations indicate that the function of slope is not a sensitive one, and the relations change monotonically with slope. But the error in the measurement of the drainage area has to be within tolerable limits for reliable estimates of discharge.

TABLE 8

URBAN LAND USE AND PERCENT OF IMPERVIOUSNESS

Land Use	Percent of Imperviousness
Industrial/Commerical/Business	80 - 90
High/Density Residential	30 - 40
Medium Density Residential	25 - 35
Low Density Residential	20 - 30

Legend: Land Use/Land Cover

I: Industrial/Commercial
U1: Dense Urbanization
U2: Medium Urbanization
U3: Low Urbanization
G: Open Grassland
F: Dense Forest

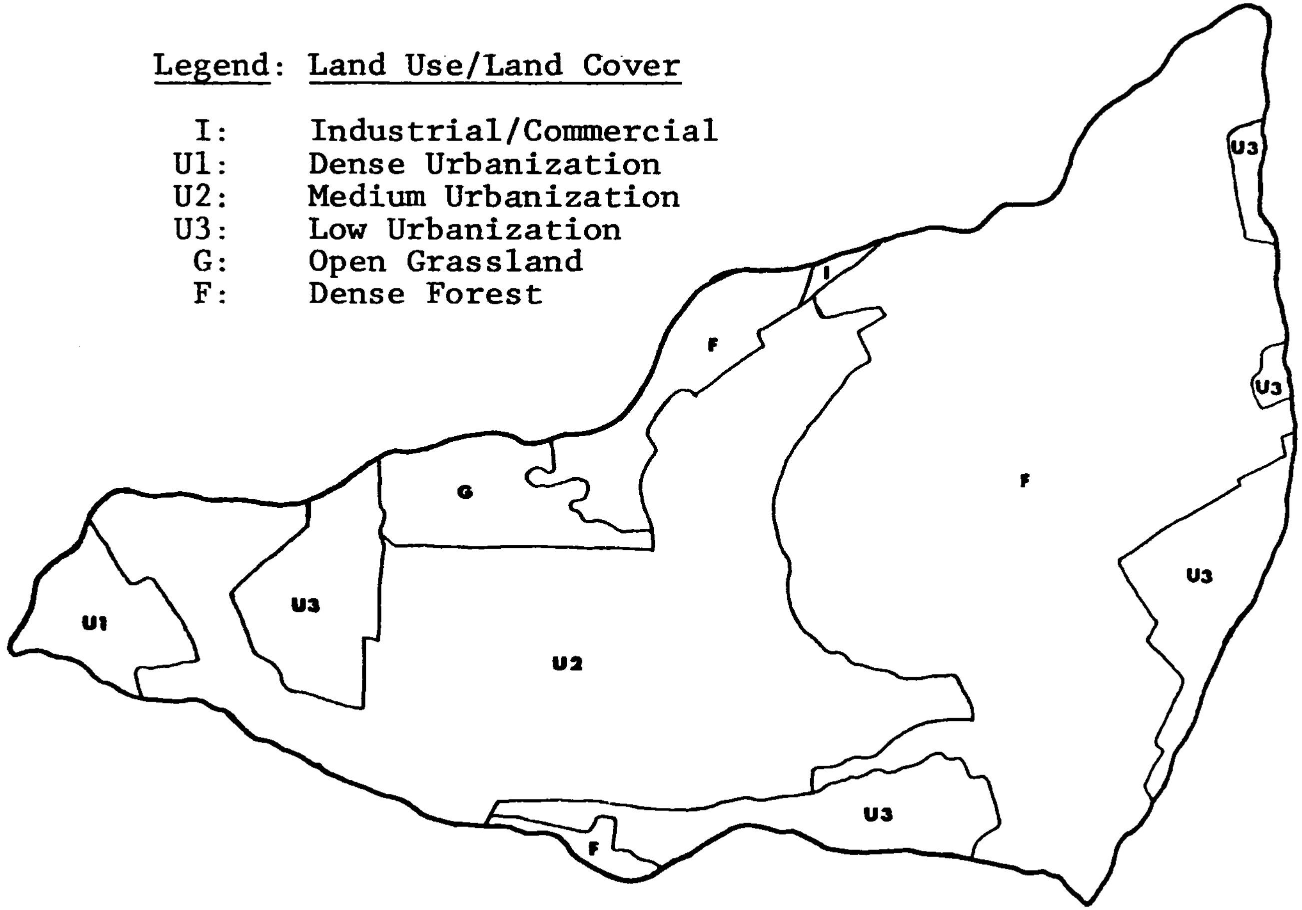


FIGURE 13. LAND USE LAND COVER CLASSIFICATION MAP OF FAGAN CREEK WATERSHED.

Approximate Scale: 1:105600.

TABLE 9

FAGAN CREEK--CALCULATION OF WEIGHTED PERCENT OF IMPERVIOUSNESS

Land use/ Land cover	Area (Acres)	Per-cent Area	Percent Imperviousness* (I)	Weighted Percent of Imperviousness
Industrial Commercial	5.7	0.21	85	0.18
Dense Urbaniza-tion	79.6	2.93	35	1.03
Medium Urbaniza-tion	929.0	34.15	30	10.25
Low Urbaniza-tion	362.7	13.34	25	3.34
Open Grassland	102.4	3.76		
Dense Forest	1240.6	45.61		

*Mean from range indicated in Table 8 was selected. Urbanized area = 1377.0 (50.63% of total watershed area).

2. Urbanization of steeper areas can result in greater peak discharge than that on gently sloping land if design and building codes are the same in both areas.

3. The percent of imerviousness and the area under storm sewerage significantly increase the peak discharge from urbanized areas.

Estimation of Percent of Area Served by Storn Sewers (D)

From Table 8 is is seen that the urbanized area is a little over 50 percent of the total watershed area, which are well served by storm sewers. Though selecting D = 100 percent seems reasonable, a factor of 80 percent was chosen for calculation.

Weighted percent of area under storm sewers (D):

$$= \frac{(50.63)(80)}{100} = 40.65.$$

Compensating for any underestimations and other assumptions, a final value of D = 45 percent was chosen arbitrarily.

For I = 15 percent and D - 45 percent.

R_L = 2, referring to Leopold curves, Figure 10.

The peak discharges for different flood frequencies are computed under natural conditions, (Q_t), which is extended to present urbanized conditions, $Q_t(u)$, applying equations as in Table 6 and the following equations:

$$Q_2(u) = R_L Q_2$$ (For annual floods under urbanized conditions)

$$Q_t(u) = \frac{7R_t Q_2 (R_L - 1)}{6} + \frac{Q_t(7 - R_L)}{6}$$

(For higher flood frequencies under urbanized conditions) (Sauer, 1974)

where

t = recurrence interval (years)

R_t = rainfall intensity, from Table 7

$Q_t(u)$ = peak discharge (ft^3/s) for recurrence interval (t) years.

Fagan Creek: Drainage area = 4.25 square miles. I = 15 percent, D = 45 percent, R_L = 2. Flood discharge in cubic feet per second (ft^3/s). Further, the flood frequencies are estimated for a future urbanized condition: I = 30 percent, D = 60 percent, R_L = 2.6. All computations are tabulated in Table 10 and Table 11. The urban flood frequency curves are shown graphically for both Table 10 and Table 11 in Figure 14.

Since the flood frequency estimations are more meaningful for small watersheds, they are computed for two sub-watersheds for Fagan Creek with contrasting

TABLE 10

FAGAN CREEK--FLOOD MAGNITUDE AND FLOOD FREQUENCY

Flood Frequency	Natural (ft^3/s)	Present Urbanization (ft^3/s)	Future Urbanization (ft^3/s)
Q_2	850.3	1700.6	2210.8
Q_5	1266.7	2341.0	2988.1
Q_{10}	1551.4	2805.5	3561.0
Q_{25}	1908.9	3389.9	4252.3
Q_{50}	2187.5	3859.2	4866.6
Q_{100}	2451.8	4257.1	5345.2

TABLE 11

PERCENT INCREASE IN PEAK DISCHARGE DUE TO FUTURE CONDITIONS

Flood Frequency	Present Urbanization (ft^3/s)	Future Urbanization (ft^3/s)	Percent Increase in Peak Discharge
Q_2	1700.6	2210.8	30.0
Q_5	2341.0	2988.1	27.6
Q_{10}	2805.5	3561.0	27.0
Q_{25}	3389.9	4282.3	26.3
Q_{50}	3859.2	4866.6	26.1
Q_{100}	4257.1	5345.2	25.1

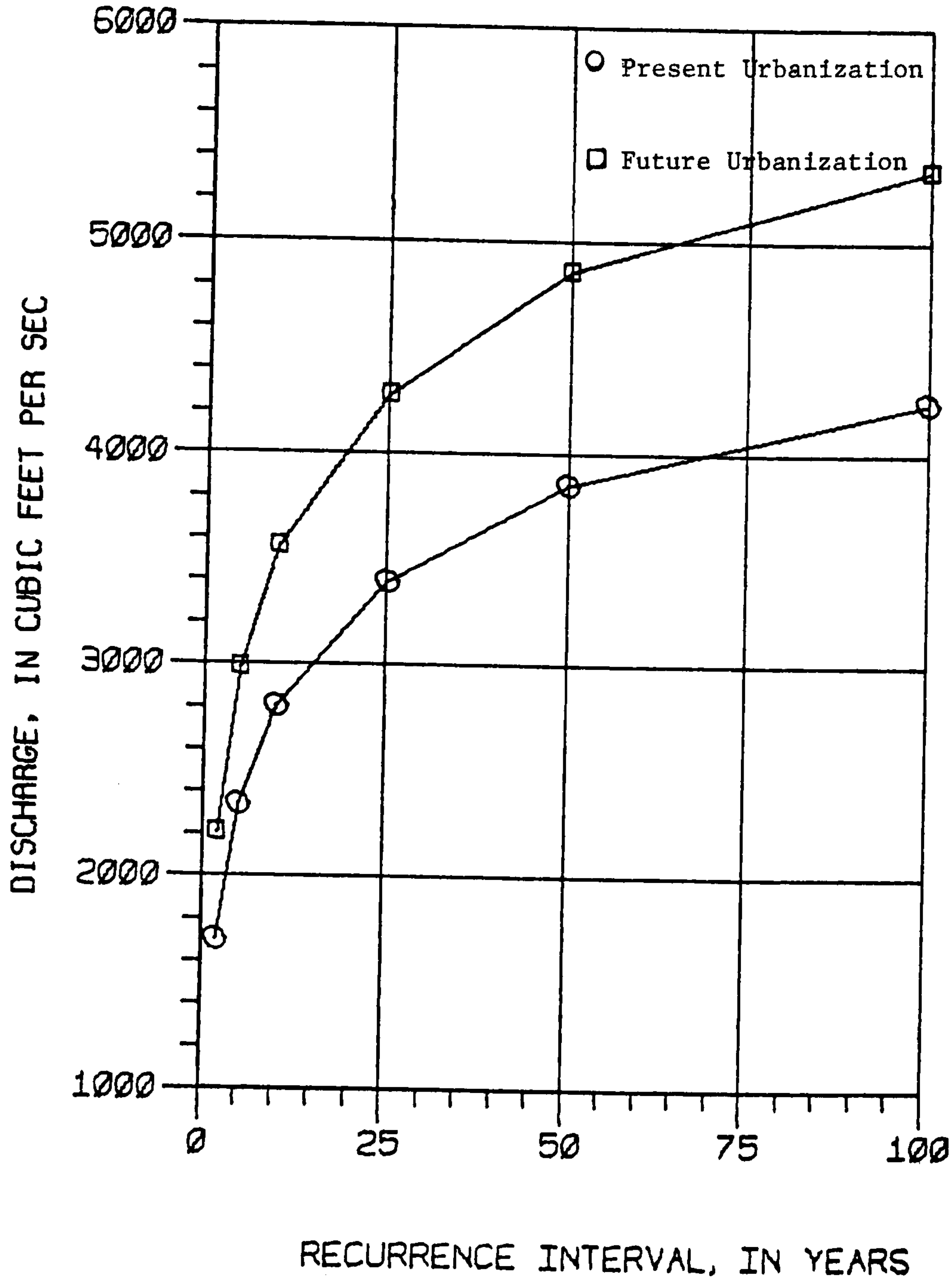


FIGURE 14. FLOOD FREQUENCY CURVES FOR FAGAN CREEK WATERSHED.

topography, land cover and soil: Mountainbrook (marked V) and sub-basin (marked U) in Figure 11.

The area in U is flat-to-rolling, dense-medium urbanized and has generally medium drained soils; while that in area V is steep, with dense vegetation and soils with steep phases and rock debris which generally have excessive drainage and rapid permeability. The flood frequencies were estimated, as previously, for: (1) sub-basin U to determine the magnitude of the runoff volumes and peak discharges; and (2) sub-basin V under its present (predominantly natural) condition and for an expected future developed condition. Sub-basin U: Drainage area = 1.14 square miles; main channel slope = 31.2 feet/mile and I = 75 percent and D = 75 percent. Sub-basin V: Drainage area = 0.25 square mile and main channel slope = 1103 feet/mile.

The results are tabulated in Table 12 and Table 13 and graphically represented in Figure 15 and Figure 16.

Fagan Creek--Estimation of SCS Runoff Curve Numbers

The development and application of the SCS runoff equation was discussed in Chapter II. A preliminary analysis indicated the following points:

1. The accurate estimate of curve number is important for both urban (high percent of impervious area) and rural (low percent of imperviousness) watersheds, for errors in runoff volume to be within tolerable limits.

TABLE 12

SUB-BASIN U; FLOOD FREQUENCY

Flood Frequency	Natural Condition (ft^3/s)	Present (Urbanized) Condition (ft^3/s)
Q_2	210.8	1011.8
Q_5	353.1	1345.8
Q_{10}	445.9	1594.9
Q_{25}	574.3	1913.5
Q_{50}	677.2	2175.8
Q_{100}	789.9	2385.8

TABLE 13

SUB-BASIN V; FLOOD FREQUENCY

Flood Frequency	Present Condition (ft^3/s)	Future Condition (ft^3/s)	Percent Increase (ft^3/s)
Q_2	199.7	299.6	50.0
Q_5	249.6	381.1	52.7
Q_{10}	278.9	434.8	55.9
Q_{25}	310.5	497.7	60.3
Q_{50}	322.9	546.3	64.1
Q_{100}	355.5	588.0	65.4

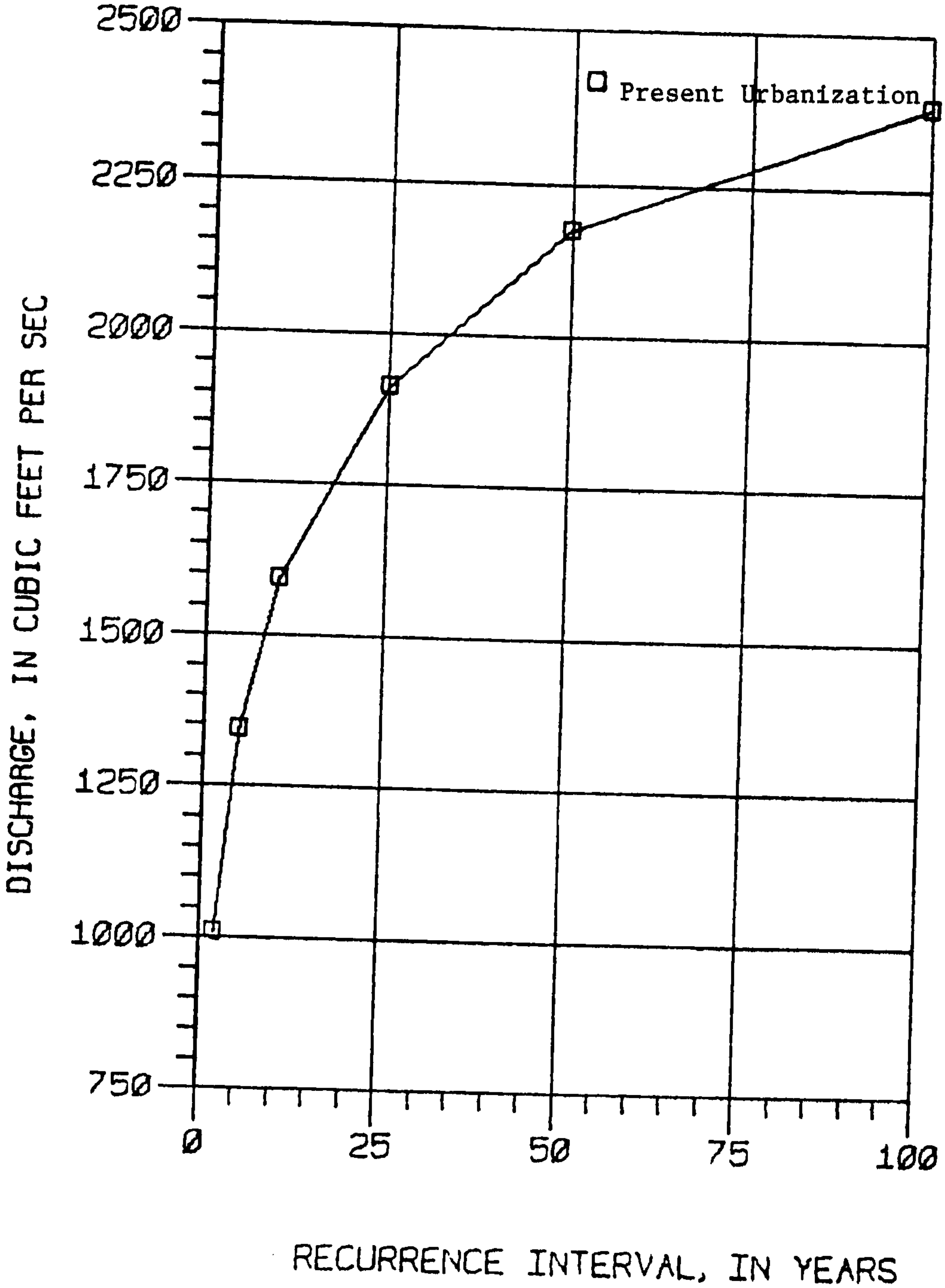


FIGURE 15. FLOOD FREQUENCY CURVES FOR SUB-WATERSHED U.

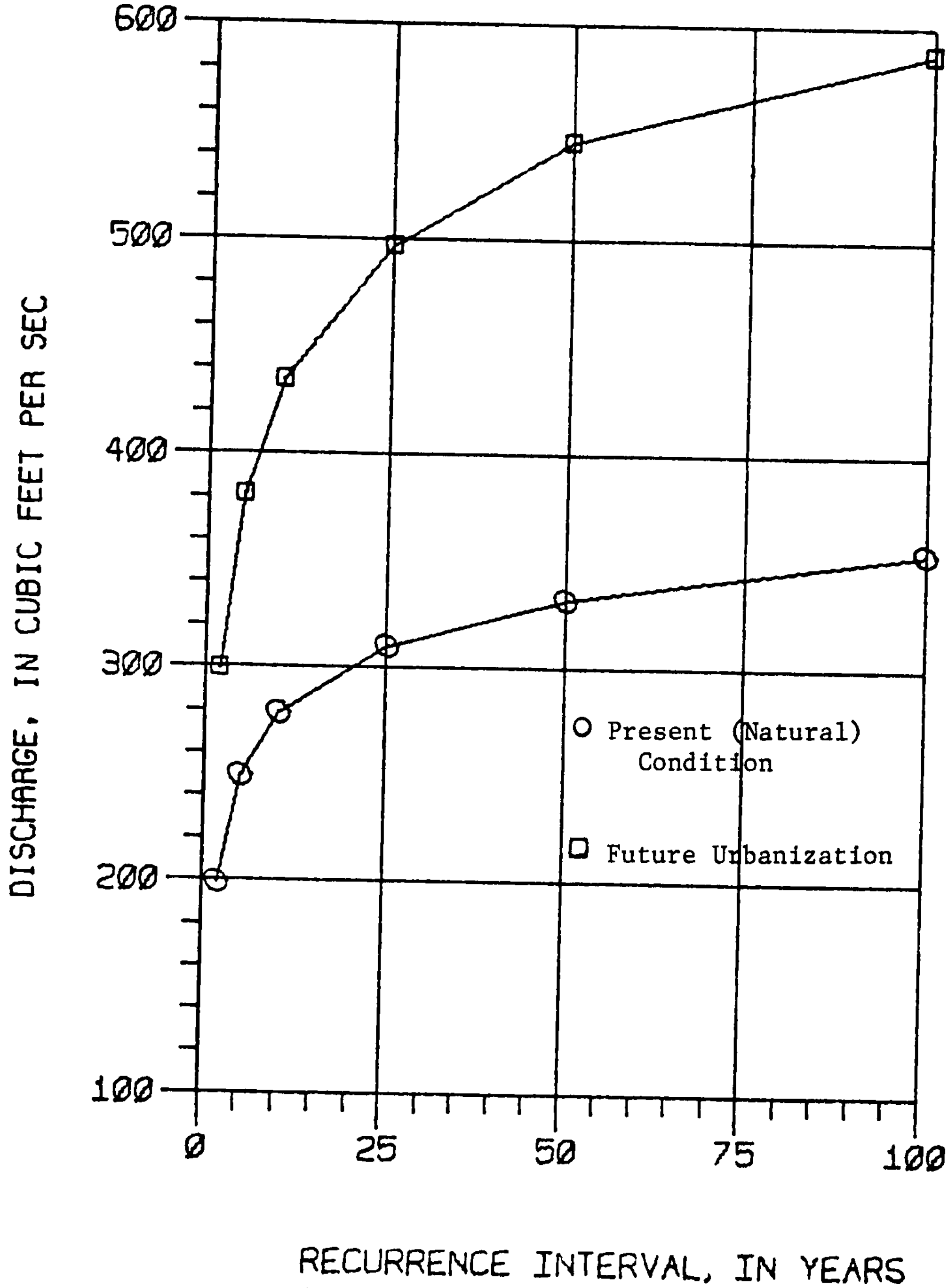


FIGURE 16. FLOOD FREQUENCY CURVES FOR SUB-WATERSHED V.

2. Errors in curve number are critical for storms of high intensity and short duration (rain depths < 10 inches).

3. Errors in rainfall and curve number are more critical for rural than urban watersheds.

4. Though rainfall data is significant, assuming a high accuracy and reliability of instrumented gage records, errors are minimized; but accurate estimation of curve numbers seems to be the weak link.

Method

Initially a soil association map, Figure 17, and a soil map, Figure 18, were prepared from the two data sources: (1) Soil Survey, Madison County, Alabama (1958), and (2) Geological Survey of Alabama, Atlas Series 8, (1975). A hydrologic soil group map, Figure 19, was prepared from these soil data and with reference to: National Engineering Handbook Section 4, Hydrology, Mockus, 1964). A brief description of the soils and their properties are listed in Table 14 and Table 15.

Next a working table relating land use and land cover, hydrologic soil groups and curve numbers, Table 16 was prepared, based on the more complex SCS Table, (Table 4, p. 51). This table is compatible with the type of remotely sensed data used in this study and classifications done.

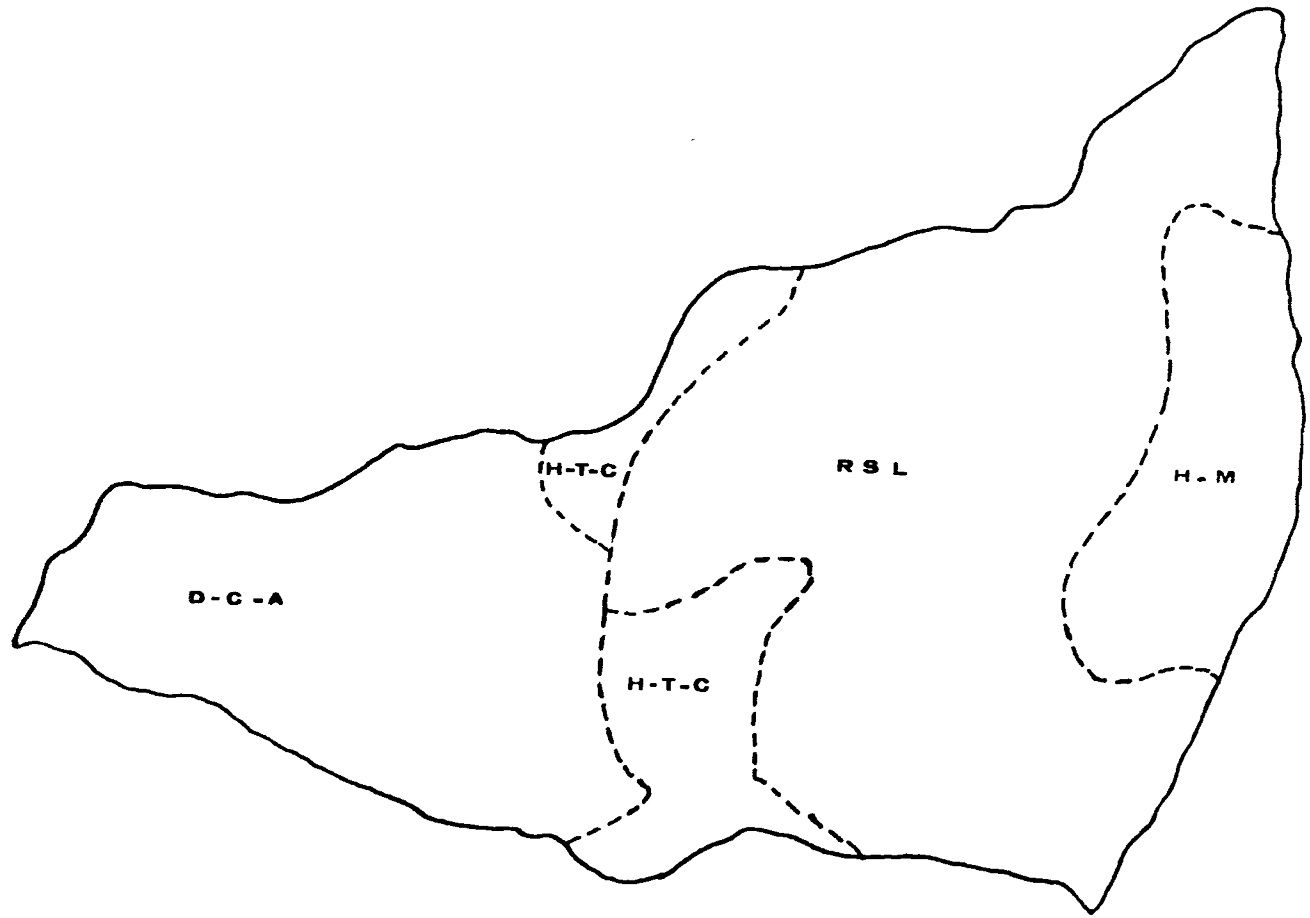


FIGURE 17. SOIL ASSOCIATION MAP OF FAGAN CREEK WATERSHED.

Source: "Environmental Geology and Hydrology, Huntsville and Madison County, Alabama"; Geological Survey of Alabama, Atlas Series 8, 1975.

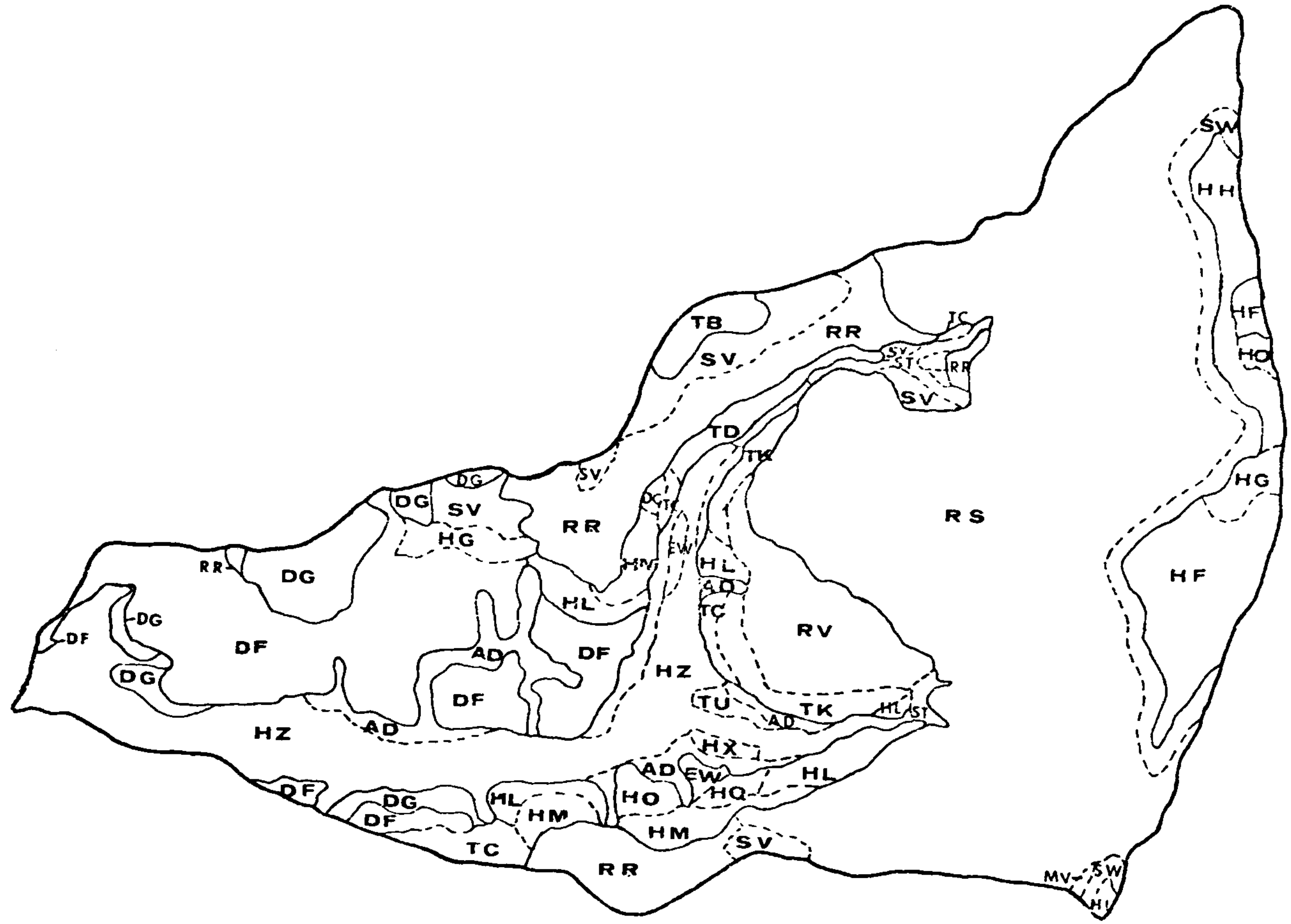


FIGURE 18. SOIL MAP OF FAGAN CREEK WATERSHED.

Source: "Soil Survey"; Madison County, Alabama, USDA/SCS, 1958.

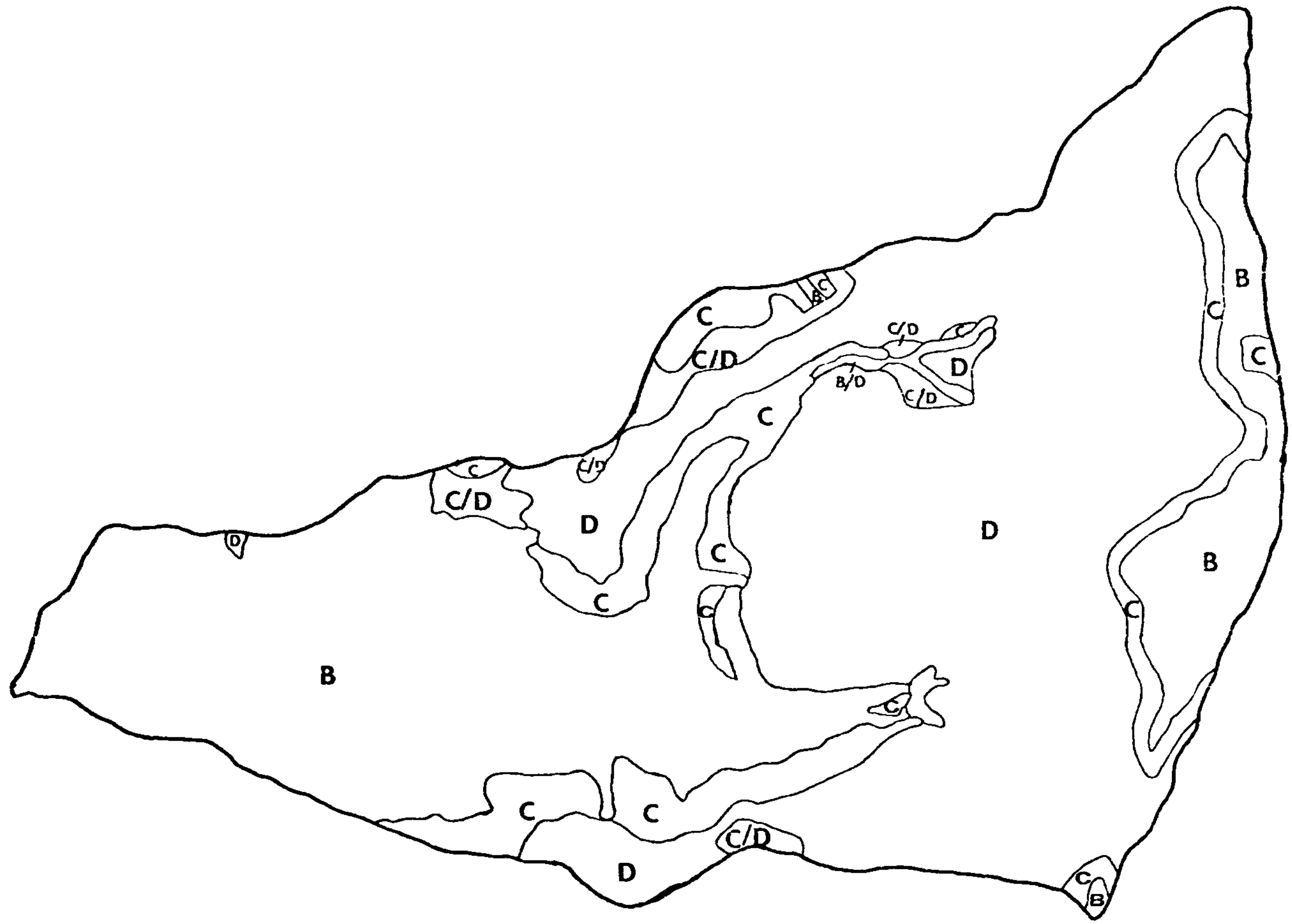


FIGURE 19. HYDROLOGIC SOIL GROUP MAP OF FAGEN CREEK WATERSHED.

Approximate Scale: 1:105,600
Group D: Hypothesized.

TABLE 14

FAGAN CREEK WATERSHED--SOIL ASSOCIATION DATA

Soil Association	Property
D-C-A Decatur-Cumberland-Abernathy	Generally well drained, red fertile soils that are thick over limestone bedrock. Found on nearly level to gently rolling terrain.
H-T-C Hermitage-Talbott-Colbert	These are thin, have a clayey texture and slow permeability. Generally occur on the slopes adjacent to steep mountainous areas.
RSL Rough Stoney Land	These are thin and occupy steep mountain slopes underlain by sandstone on the upper slopes, and by limestone on the lower slopes. Slopes are generally covered by rock debris.
H-M Hartsell-Muskingum	Well drained, sandy, thin, and underlain by sandstone and located on undulating to strongly rolling isolated ridgetops of steep mountains.

TABLE 15

FAGAN CREEK--SOILS AND SOIL HYDROLOGIC GROUP

	Soil	Symbol	Hydrologic Group
1.	Decatur and Cumberland silty clay, loams, eroded undulating phases	DF	B
2.	Decatur and Cumberland silty clay loams--eroded rolling phases	DG	B
3.	Hartsells fine sandy loam, rolling phase	HF	B
4.	Hartsells fine sandy loam, eroded rolling phase	HF	B
5.	Hermitage cherty silt loam, eroded rolling phase	HL	C
6.	Huntington silt loam	HZ	B
7.	Rockland, limestone, hilly	RR	A/B(D*)
8.	Rockland, limestone, steep	RS	A/B(D*)
9.	Abernathy silt loam	AD	B
10.	Allen fine sandy loam, eroded rolling phase	AO	B
11.	Decatur and Cumberland silt clays, severely eroded undulating phases	DC	B
12.	Decatur and Cumberland silty clays, gullied phases	DE	B
13.	Dickson silt loam, level phase	DS	C
14.	Etowah silt loam, level phase	EW	B

TABLE 15 (continued)

	Soil	Symbol	Hydrologic Group
15.	Hartsells fine sandy loam, eroded rolling phase	HG	B
16.	Hartsells fine sandy loam, rolling shallow phase	HH	B
17.	Hartsells fine sandy loam, eroded rolling shallow phase	HI	B
18.	Hermitage cherty silt loam, eroded hilly phase	HM	C
19.	Hermitage silt loam, undulating phase	HO	C
20.	Hermitage silt loam, eroded rolling phase	HQ	C
21.	Humphrey's silt loam	HX	B
22.	Muskingum stony fine sandy loam, hilly phase	MV	C
23.	Ooltewah silt loam	OP	C
24.	Stony colluvium, Jefferson and Colbert soil materials	ST	B/D
25.	Stony rolling land, Talbott and Colbert soil materials	SV	C/D
26.	Stony steep land, Muskingum soil materials	SW	C
27.	Talbott cherty, silty clay loam, eroded undulating phase	TB	C
28.	Talbott cherty silty clay loam, eroded rolling phase	TC	C
29.	Talbott silty clay loam, eroded undulating phase	TG	C

TABLE 15 (continued)

	Soil	Symbol	Hydrologic Group
30.	Talbott, Colbert cherty silty clay loams, eroded hilly phases	TK	C/D
31.	Talbott cherty silty clay severely eroded roll phase	TD	C
32.	Tupelo silt loam	TU	D

*The hydrologic soil group for these soils were not available from the soil data. Though Group A or Group B seem appropriate, Group D was selected for this study to evaluate the effect of poor drainage under certain developed conditions (hypothesized). The exact group has to be verified for accurate estimation of the "CN" for these soils.

NOTE: Numbers one through eight are major soils and numbers twelve through thirty two are minor soils.

TABLE 16

RUNOFF CURVE NUMBERS FOR SELECTED LAND USES

Legend	Land Use Description	Hydrologic Soil Group A	B	C	D
I	Industrial Districts (72% impervious)	81	88	91	93
U1	Dense Urbanization Commercial and Business areas (85% impervious)	89	92	94	95
U2	Medium Urbanization (38% impervious)	61	75	83	87
U3	Low urbanization (30% impervious)	57	72	81	86
G	Open grassland, open spaces, lawns, parks, golf courses, cemeteries, etc. Fair condition; Grass cover on 50% to 75% of the area	49	69	79	84
F	Forest cover, dense cover	25	55	70	77

A grid is overlaid on the land use and hydrologic soil group maps. The size of the grid is arbitrary, and it facilitates interaction of the map data with gridded watershed models. Each character on the classification map represents a spectral response to a land cover condition. From a knowledge of land use and soil group data, an average curve number is assigned to each grid cell, referring to Table 16.

Each cell is thus designated resulting in a map of distributed curve number values for the watershed. Figure 20 shows the final grid curve number map for the whole watershed. The steep soils of the slopes of the watershed were classified in hydrologic soil group D, for curve number estimation in this study, but this could not be verified from available soil data. Though group A or group B is more appropriate, group D was chosen as a hypothetical case. Hence, the curve number estimations are overestimated. But the methodology and effects of land use and vegetative cover on curve number are similar. One advantage of such a method is the information provided on the sources of potential runoff from different areas in the watershed. Figure 21 depicts suitable zoning of the areas of the watershed, based on the different ranges of the curve numbers. Figure 22 shows the gridded curve number distribution for sub-watersheds V and W. Thus, runoff potential of different sub-watersheds

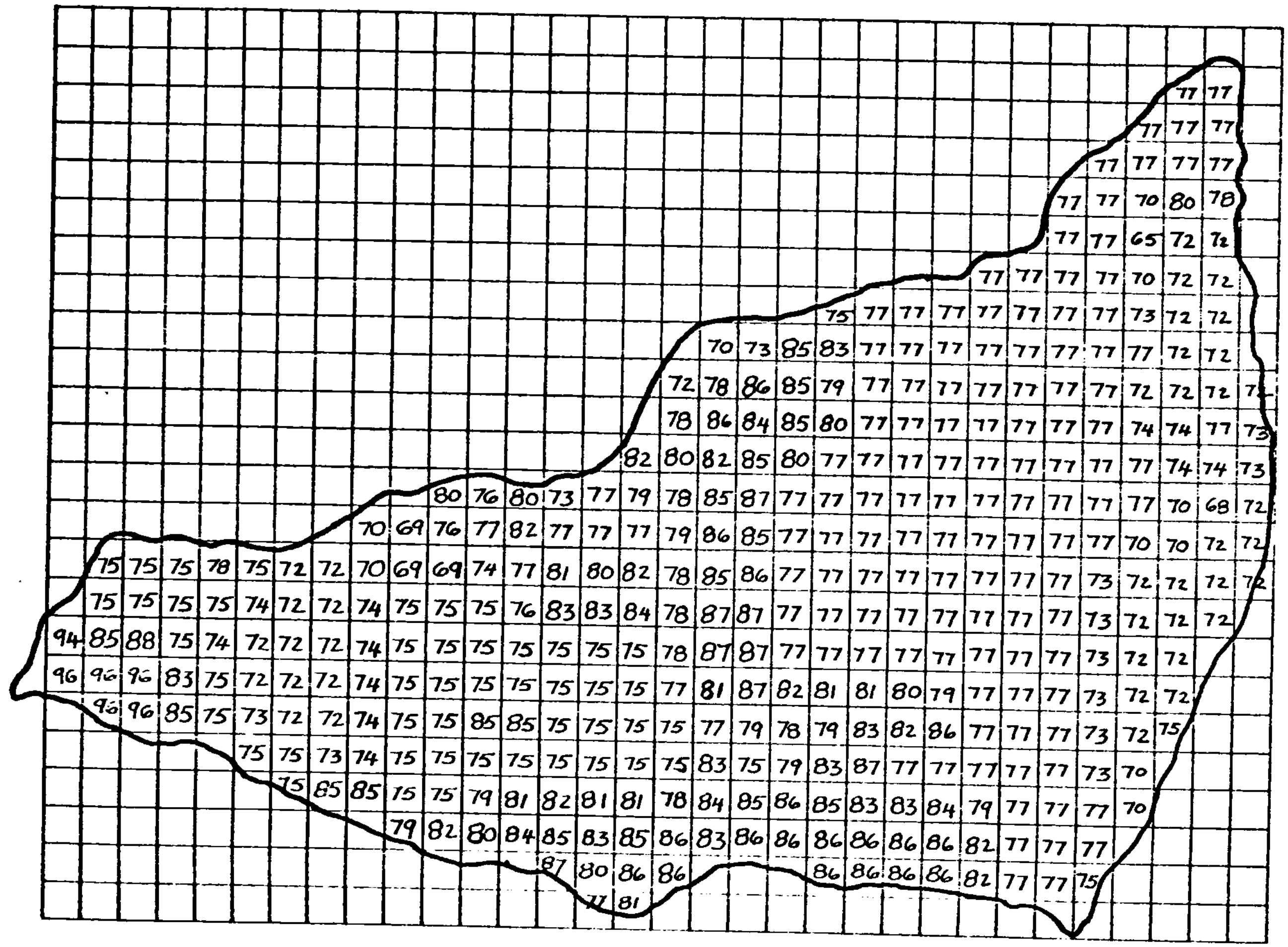


FIGURE 20. MAP OF DISTRIBUTED CURVE NUMBERS OF FAGAN CREEK WATERSHED.

Zone	Curve No
Z1	> 90
Z2	81 - 90
Z3	71 - 80
Z4	61 - 70

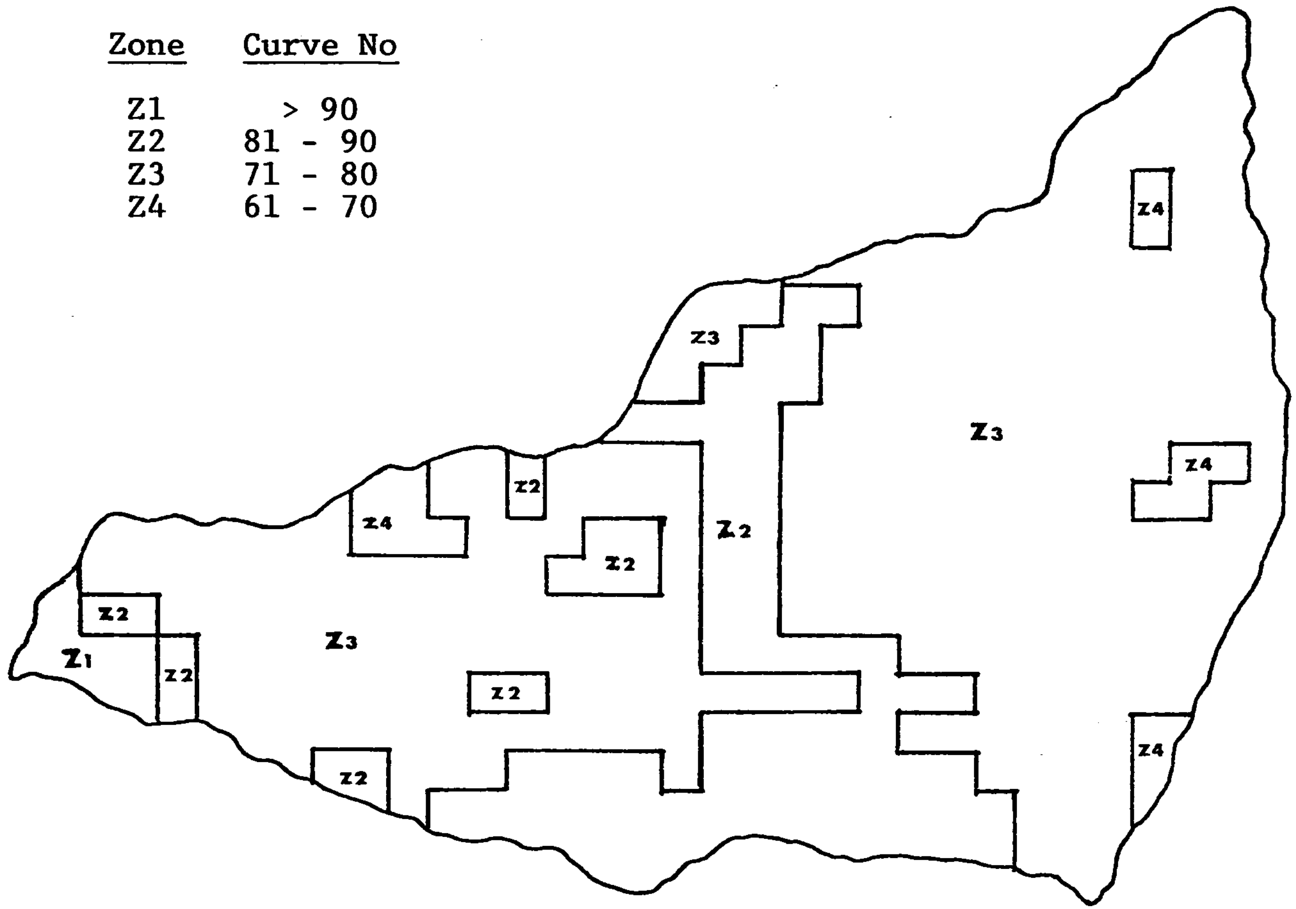


FIGURE 21. ARBITRARY ZONING OF RUNOFF POTENTIAL AREAS OF FAGAN CREEK WATERSHED.

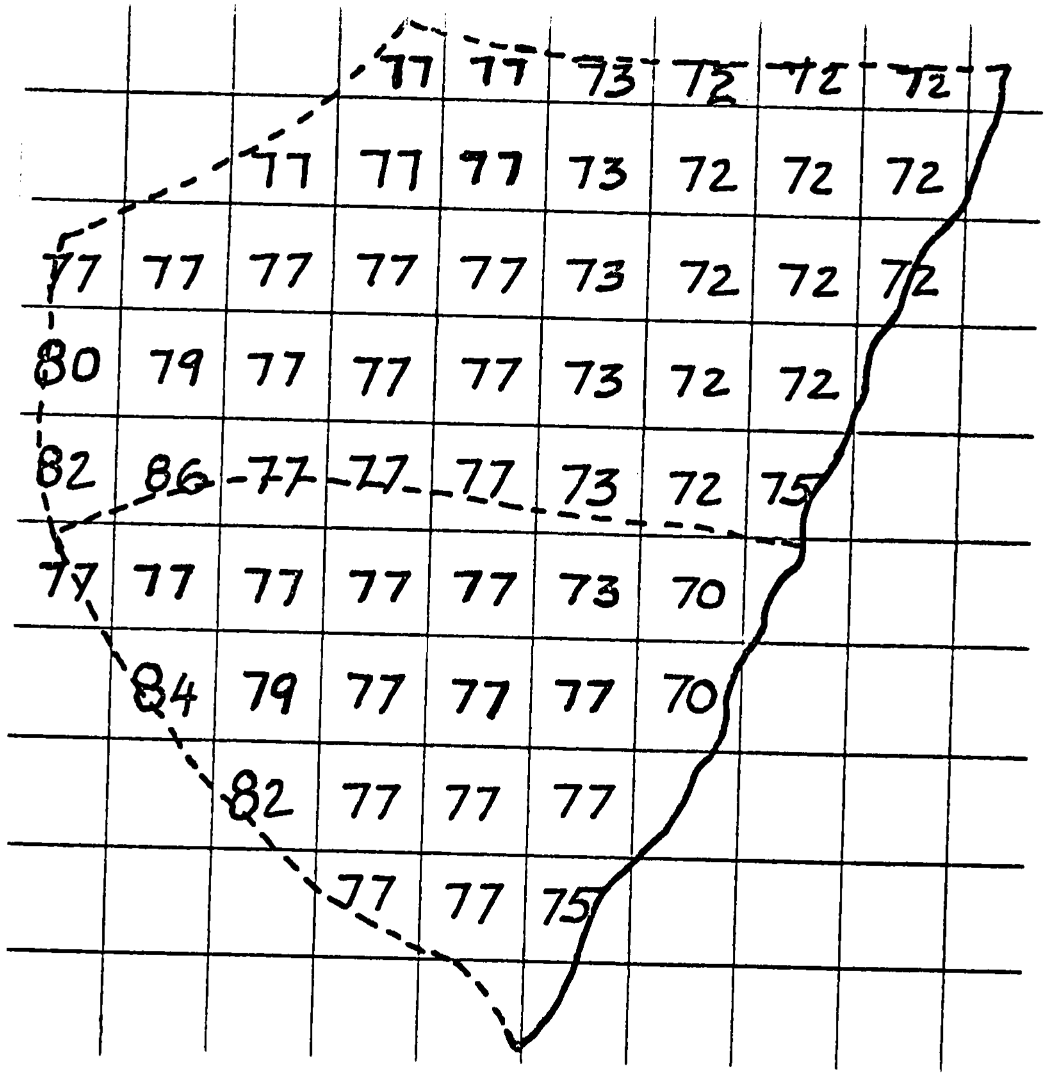


FIGURE 22. DISTRIBUTED CURVE NUMBER MAP OF SUB-WATERSHEDS V AND W.

can be estimated, which can be input to more complex models.

In this research study, a simple FORTRAN program was developed to generate grids of variable sizes using the built in subroutines of The University of Tennessee Space Institute (UTSI) computer system. A program was also developed to calculate the maximum, minimum, and weighted averages of the curve numbers of the grid system. These are included in Appendix B.

An estimate of the erosion potential of steep slopes was also evaluated. One measure is by applying the universal soil loss equation (USLE) A - RKLSCP, where the soil loss (A) depends on the factors: rainfall (R), soil erodibility (K), ground slope length (L), ground slope (S), cropping management (C) and erosion control practice (P).

The factors (L) and (S) are combined and expressed as:

$$LS = \left(\frac{L}{72.6}\right)^{m} (0.065 + 0.045S - 0.0065S^2)$$

where

LS = topographic factor for use in USLE

L = slope length (feet)

S = percent slope

$m = 0.3$ for flatter slopes

$m = 0.5$ for $S > 3$ percent

The (LS) factor is significant in the soil loss estimation since it accounts for more variation in gross erosion than any other factor. Of the two factors, slope length and percent slope, the latter is more significant in (USLE) estimations. Since the (USLE) was designed for small size agricultural fields, normally (L) and (S) are determined by field survey methods. But such methods are difficult, if not impracticable, in watersheds of complex topography. In these cases sample areas are surveyed, and soil maps are often used to determine the average slope length (L) and gradient (S). The measurement can be done quickly and accurately from USGS topographic maps, which are derived from aerial photographs.

Sub-basin V

Average watershed slope was determined by both using a slope indicator which can be directly used on topographic maps and also by the contour length method:

$$\text{Average percent slope (S)} = \frac{0.25H(CL_{25} + CL_{50} + CL_{75})}{DA}$$

where

H = total watershed relief,

CL_{25}, CL_{50}, CL_{75} = contour length at 25, 50 and 75 percent of (H)

DA = drainage area.

$$\text{Average slope length (L)} = \frac{1}{2D_d\sqrt{1 - \frac{S_{ch}}{S_{gr}}}}$$

where,

$$D_d = \frac{\Sigma L}{DA}$$

D_d = drainage density (stream lengths per unit area)

ΣL = total stream lengths in the area.

S_{ch} = main channel slope

S_{gr} = average ground slope.

Estimating:

DA = 0.25 square mile

ΣL = 0.62 mile

Dd = 2.46

Average channel slope = 20.9% ≃ 21%

Average ground slope = 28.3% ≃ 30%

Average slope length = 0.68 ≃ 0.7

For a slope length, L = 0.7 the (LS) factor is calculated for different percent slopes, Table 17.

TABLE 17

(LS) FACTOR FOR DIFFERENT PERCENT SLOPES (S)

Percent Slope (S)	(LS) Factor
5	0.04
10	0.11
15	0.22
20	0.35
25	0.52
30	0.71
35	0.94
40	1.20
45	1.50
50	1.82

It is seen that the (LS) factor increases appreciably with increase in slope percent, which is thus a significant factor in the soil loss equation. The effect is shown graphically in Figure 23, where the slope of the curve is high at about 40 percent slope and above. This consideration is important, as it indicates how soil

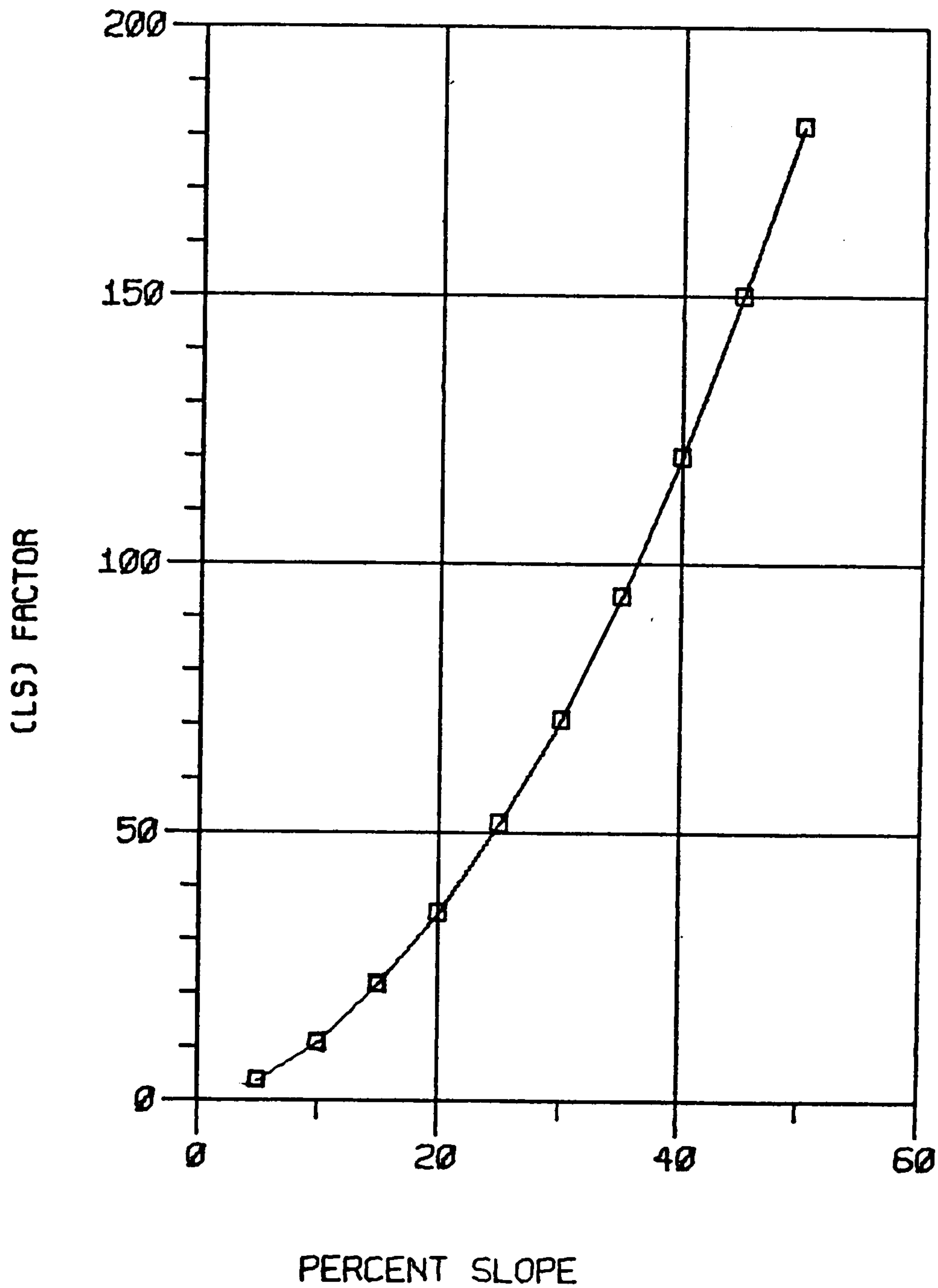


FIGURE 23. VARIATION OF TOPOGRAPHIC FACTOR (LS) WITH SLOPE GRADIENT (S) FOR SUB-WATERSHED V.

loss increases dramatically with slope. Such factors are to be considered on soils of such steep slopes as Mountainbrook, which are characterized by limestone outcrops, rock debris and loose fragments and are erosive.

The dense vegetation plays a vital role on such steep soils. It reduces the eroding effect of intense rain by absorbing the kinetic energy of the raindrops, while the forest litter reduces splash erosion and prevents lateral movement of soil particles down the slope. Thus, forest cover affects the slope soil and hydrology.

Hence new urban developments should consider such environmental factors and its impact on hydrology, erosion, sedimentation in drainage channels, etc.

CHAPTER IV

APPLICATION OF REMOTE SENSING IN HYDROLOGIC SIMULATION MODELS

Hydrologic simulation models find extensive application in water resources management; for example in the simulation of the watershed processes, streamflows or water quality parameters under different watershed conditions. In addition to the two general categories of models, "Parametric" and Stochastic" models , they are also classified as "Management" and "Planning" models. Management models are suitable for long range rainfall, runoff and water resources studies, while planning models are applied for estimation of the effects of short lived events, (e.g., runoff and peak discharge due to storms of high intensity and short duration). The historical development, verification and application of remote sensing based mathematical models has been documented by several research works and projects (Ambaruch, 1973), Fowler (1977), Ragan (1977) and others. Most of the models developed were applicable for watersheds with a historical rainfall-runoff data. Thus, by verification and validation for these data, they were extended to other ungaged watersheds, having similar characteristics. Many of the models available today are not amenable to remote sensing methods. But the need for newer models that can be applied to partially gaged (or ungaged) watersheds have led to present models that can be interfaced with remote sensing capabilities. These have several advantages; remote sensing can:

1. provide timely hydrologic data;

2. yield parameters which can be easily derived in terms of the land use, land cover, percent of imperviousness, curve number, etc.;

3. allow experimentation with alternate forms of watershed development and the assessment of future changes that might occur;

4. be particularly advantageous for ungaged watersheds;

5. create potential for newer models with more parameters amenable by remote sensing;

6. be rapid and cost-effective.

Several hydrologic models for specific studies are available: EPA "Storm Water Management" model for urban studies, SCS "Storm" runoff model, strip hydrograph model (Fowler, 1977), etc.

Several investigations in hydrologic modelling, (e.g., by Blanchard (1975), Ragan and Jackson (1976)), have demonstrated the feasibility of applying remotely sensed data to existing models with great accuracy. For large watershed analysis Landsat digital data and computer-aided analysis are essential, which further facilitates work from a large area data base.

Though most inputs to hydrologic models are presently from land use/land cover information, the more reliable information on soil properties. (e.g., soil moisture capacity) and quantitative measurements would improve the predictive power of the models. This would also need interfacing hydrologic data from several different sources, wherein lies the versatility of hydrologic models.

Strip Hydrograph Model

The strip hydrograph model is a hydrologic planning model, that is widely applicable for gaged and ungaged watersheds, predominantly rural. A complete description of the development, formulation, verification and validation of the model is contained in the reports (Fowler, 1975, 1976, 1977). It is particularly suitable for use with input parameters derived from remotely sensed data, both the watershed physiographic (area, drainage density, etc.) and hydrologic data (e.g., Manning's roughness coefficient). Methods for extraction of hydrologic data and quantification of parameters of the model are also explained in the reports. Their study has established the feasibility of using remote sensing in the extraction of the hydrologic data to the required accuracy. It incorporates such factors as slope, surface roughness, and soil moisture which drive (control) the hydrologic processes of infiltration and overland flow.

This model is a part of a more comprehensive model, consisting of two modules--overland flow module and the channel routing module.

The overland flow module simulates the flow of rainfall over the watershed surface, subjects it to sub-surface abstraction (using Holtan's infiltration formula, expresses coverage infiltration as a function of vegetation cover cover index soil moisture capacity, cumulative infiltration and saturated infiltration rates); and routes the excess through stream channels to the outlet. The factors explicitly considered are: surface cover, land use, soil type, soil moisture content, watershed and channel physiography, and topography.

The overland flow module computes the discharge (runoff rate) by using Manning's formula for surface flow:

$$Q = \frac{\sqrt{S}}{n} (y)^{2/3}$$

where

Q = surface runoff (m^3/sec)

S = ground slope (m/m)

n = Manning's surface friction coefficient

y = depth of overland flow (m).

The model operates in discrete time steps, computing a depth value (y) for each time interval, and using their average to calculate a discharge (Q). The output overland flow hydrograph is constituted by these incremental (Q) values.

The channel flow module takes the overland hydrographs from homogeneous sub-areas of a watershed and routes them to the outlet. Manning's relation (for channels) is used to compute the total channel outflow. Table 18 summarizes the model's components.

Discussion of the whole model is beyond the scope of this study. However, the application of the strip hydrograph model has been demonstrated for a small test watershed. A "FORTRAN" listing of the same is included in Appendix A.

The output hydrograph is obtained both in tabular form and an optional graphical form.

An example of the application of the overland flow module is demonstrated to a small watershed, upstream Aldridge Creek. The analysis is only preliminary tests, to demonstrate the application of remote sensing.

The soil parameters: soil moisture capacity, percolation rate and infiltration capacity were hypothesized for each strip area.

From the rainfall-runoff data for March 15 to March 17, 1973 at the gaging station (03575686), at the

TABLE 18

STRIP HYDROGRAPH MODEL

Model Components	
<u>Overland Flow Parameters</u>	<u>Channel Flow Parameters</u>
Unit strip length, meters	Channel length, meters
Unit strip slope, meters/meter	Channel slope, meters/meters
Unit strip Manning's "n"	Channel Manning's "n"
Initial depth of flow, meters	Channel Hydraulic radius, meters
<u>Soil Parameters</u>	
Soil moisture capacity, meters/meter	
Antecedent moisture content, meters/meter	
Percolation rate, meters/second	
Steady-state infiltration rate, meters/second	
<u>Overland Flow Inputs</u>	<u>Channel Flow Inputs</u>
Rainfall temporal profile	Unit strip hydrographs
Rain rate (meter/second)	Discharge, cubic meters/second
Time (Seconds)	Time (Seconds)

outlet of the watershed, three rainfall rates were selected for this analysis: (1) 2.5 inches in 12 hours: 0.000000147 meter/second; (2) 1.0 inches in 6 hours: 0.00000117593 meter/second; and (3) 1.5 inches in 0.5 hours: 0.00002116667 meter/second.

An estimate of the factor "antecedent soil moisture" was made from recorded rainfall depths from March 5, 1973 to March 16, 1973.

Equation used: $ASM_{(n)} = P_{(n)} + 0.9\ ASM_{(n-1)}$,

where

$ASM_{(n)}$ = antecedent moisture on day (n)

$P_{(n)}$ = precipitation on day (n)

$ASM_{(n-1)}$ = antecedent moisture on day (n - 1).

The model was run with typical sets of input data for the strips: A2 (steep and predominantly rural), C (flat to moderate, urban) and D (steep to moderate, partially urban). Sample outputs are included in Appendix B. A brief discussion of the results follows in the next section.

Methodology

The primary concept is the sub-watershed, where the whole watershed is divided into hydrologically homogeneous areas (sub-basins) having uniform characteristics:

topography, soil characteristics, surface cover, etc. Once this is established average model parameters are estimated from available data or hypothesized. This method assists in determining what areas of the watershed have higher overland flow and contribute to greater runoff.

A small upstream watershed of the Aldridge Creek was selected for the study. Using 1:24,000 USGS/TVA topographic map and color infrared imagery, the subdivision of watershed and land cover classification was done. Figure 24 shows the watershed sub-basins and Figure 25, the land cover classification. Next, the watershed was divided into rectangular strips, as shown in Figure 26, which approximates the area of the corresponding sub-watersheds. This method of approximation is particularly suitable for watershed data analysis in a rectangular or square grid system for computer simulation of the watershed processes (e.g., runoff, erosion, etc.).

Knowing the percentage of area of each type of cover, a weighted average of Manning's (n) was estimated and tabulated, Table 19, referring to Table 20. The length of each strip is approximated by the average strip length. These fix the width, which is an indication of the overland flow length. An average ground slope was determined using the "slope indicator."

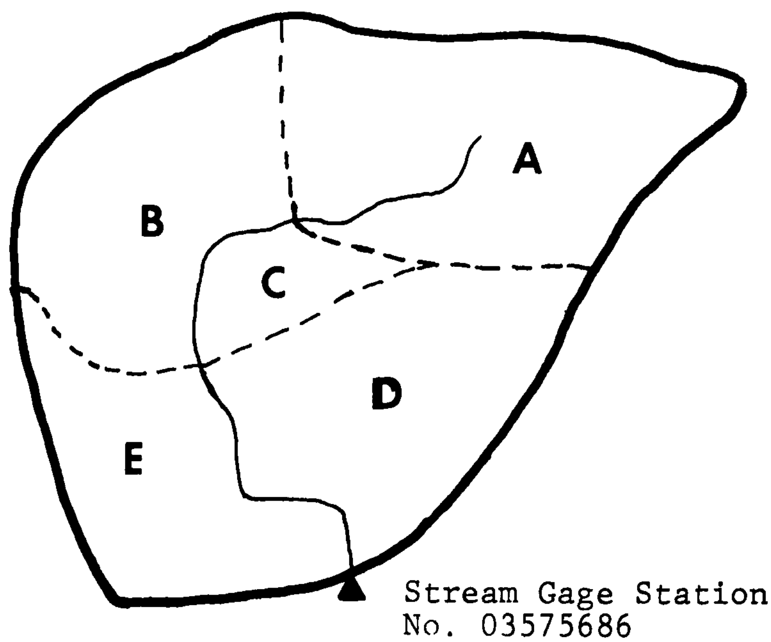
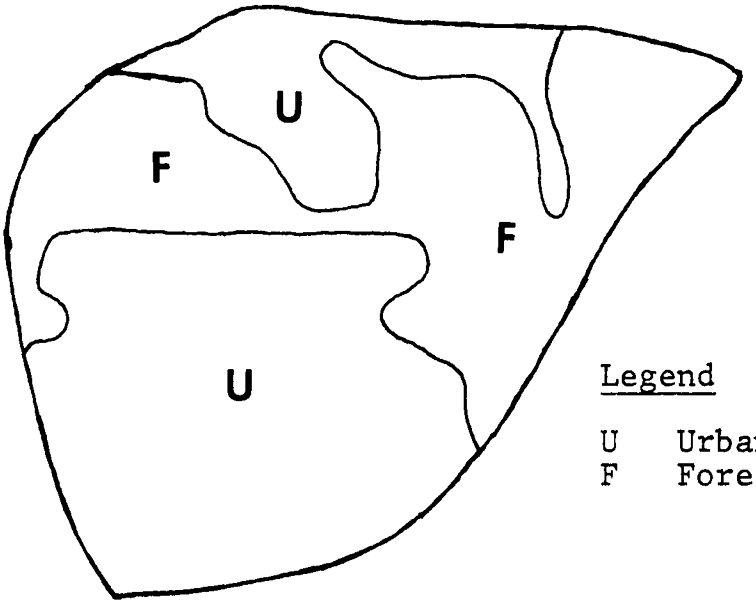


FIGURE 24. UPSTREAM ALDRIDGE CREEK WITH SUB-WATERSHEDS.

Scale: 1:24,000



Legend

U Urban
F Forest

FIGURE 25. LAND USE AND LAND COVER CLASSIFICATION MAP OF UPSTREAM ALDRIDGE CREEK.

Scale: 1:24,000.

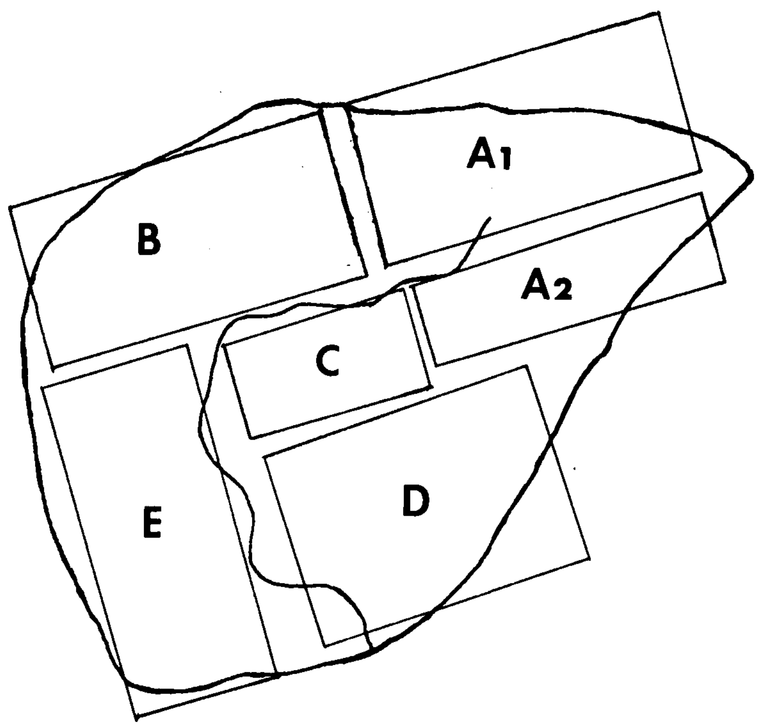


FIGURE 26. STRIP CONFIGURATION OF UPSTREAM ALDRIDGE CREEK.

Scale: 1:24,000

TABLE 19

WEIGHTED AVERAGE MANNING'S "n"

Sub-watersheds	Percent Forest (n = 0.1)	Percent Urban (n = 0.01)	Weighted Manning's Coefficient*
A1	60	40	0.064
A2	100	0	0.1
B	65	35	0.068
C	20	80	0.028
D	35	65	0.042
E	0	100	0.01

*Emphasis was on relative estimation of "n" for each sub-watershed.

TABLE 20

MANNING'S ROUGHNESS COEFFICIENT FOR OVERLAND FLOW FOR VARIOUS SURFACE TYPES

Watershed Surface	Manning's "n"
Smooth Asphalt	0.013
Concrete (Trowel Finish)	0.013
Rough Asphalt	0.016
Concrete (Unfinished)	0.017
Smooth Earth (Bare)	0.018
Firm Gravel	0.020
Cemented Rubble Masonry	0.025
Pasture (Short Grass)	0.030
Pasture (High Grass)	0.035
Cultivated Area (Row Crops)	0.035
Cultivated Area (Field Crops)	0.040
Scattered Brush, Heavy Weeds	0.045
Light Brush and Trees (Winter)	0.050
Light Brush and Trees (Summer)	0.060
Dense Brush (Winter)	0.070
Dense Brush (Summer)	0.100
Heavy Timber	0.100
Idle Land	0.030
Grass Land	0.032

Source: H. L. Loats, Jr., et al. "Applications of Remote Sensing to Hydrologic Planning," 1978. Pp. 49.

Input conditions for the test hydrograph generation were: rainfall rate 1: 0.00002000 meter/second for 1000 seconds duration; rainfall rate 2: 0.00000200 meter/second for 1000 seconds duration. Antecedent soil moisture (ASM): 0.10 meter. (Though the computer ASM was 0.23 meter, a value of 0.10 meter was selected). Table 21 lists the input data required by the model. For strip A2, the discharge peak after 100 seconds reached (.000454) m^3/s. For a steeper slope of (35 percent) the same estimate was (0.00053) m^3/s, an increase of nearly 17 percent. If under certain land use changes, Manning's n = 0.08, peak discharge reached (.00056) m^3/s, an increase of nearly 24 percent. For strip C the peak discharge is (0.0065) m^3/s. This clearly indicates the high runoff potential of urban areas.

For strip D, the peak discharge estimated is (0.00656) m^3/s. Though the catchment area and slope are higher than that for strip C, the effect of vegetative cover is to considerably reduce the overland flow (surface runoff). The effect of land use change, resulting in a roughness coefficient, n = 0.038 results in a peak discharge of (0.0068) m^3/s, an increase of only 4 percent.

Such an analysis of sub-watersheds determines both the shape of the final hydrograph, and also the sensitivity of the estimated discharge to variations in

TABLE 21

HYDROLOGIC DATA OF COMPONENT STRIPS

Strip	Length (Meter)	Width (Meter)	Area (Square Meter)	Slope	Manning's "n"	Soil Moisture Capacity (Meter)	Percolation* Rate (Meter/S)	Final* Infiltration (Meter/S)
A1	1008.0	528.0	532224.0	0.20	0.064	0.03	0.00001500	0.00002100
A2	936.0	276.0	258336.0	0.25	0.10	0.03	0.00001500	0.000021111
B	1008.0	528.0	532224.0	0.18	0.068	0.060	0.00001500	0.00002100
C	576.0	312.0	179712.0	0.12	0.028	0.010	0.00000110	0.000001056
D	864.0	648.0	559872.0	0.16	0.042	0.015	0.00000110	0.000000700
E	1056.0	456.0	481536.0	0.15	0.01	0.010	0.00000110	0.000001100

*Inf red or hypothesized from soil survey report, soil hydrologic group and the following Table:

Soil Class (Group)	Final Infiltration Rate (cm/hr)
A	1.14 - 0.76
B	0.76 - 0.38
C	0.38 - .12
D	0.12 - 0.00

Source: Castruccio P., et al; "The Application of Remote Sensing to the Development and Formulation of Hydrologic Planning Models," 1976. Pp. 29.

the input parameters. This would also set the accuracy needed of the input parameters.

Though the test watershed for the above analysis was very small, and predominantly urban or thickly forested on mountain slopes, the rainfall runoff studies of such areas are important in the hydrologic problems of the localized regions; (e.g., estimation of peak discharge at a point downstream). Again, in a network of sub-watersheds, the runoff control from steep watersheds upstream (e.g., by detention ponds) will greatly reduce flooding problems in the downstream area in many cases.

In the author's opinion, hydrologic modelling of the whole Aldridge Creek watershed is very appropriate and perhaps even necessary to arrive at better estimates of flood potential in different subcatchment areas. This would assist in the planning decisions and also to evaluate the impact of various alternatives.

CHAPTER V

SUMMARY AND CONCLUSIONS

The discussions in this study clearly emphasize the need for adequate planning in the use of a watershed's water resources, considering the combined effects of the geology, soil, hydrology and the precipitation characteristics of a geographical region.

The limitations of empirical equations in estimating flood frequencies under different land conditions have to be understood. Such estimates have to be verified by other methods.

One of the objectives of this study was to demonstrate the feasibility of using remotely sensed data (e.g., color infrared imagery) for a quick and reliable estimate of such hydrologic parameters as percent of imperviousness, SCS curve number and Manning's surface roughness coefficient factor from basic land use and land cover data. But proper methodology of such data extraction and quantification have to be established. Further, the variation of the hydrologic parameters with time necessitates temporal data. Better estimates of the parameters (particularly those related to soil properties) have to be made from several other data sources (e.g., soil moisture estimation from microwave sensors). This has to be parallelled with improved analysis techniques.

In this respect remote sensing plays a very vital role as a prime data source. The dynamic nature of the watershed can be periodically monitored.

The concept of sub-basins was emphasized for a more meaningful watershed hydrologic analysis, which gives better insight into such problems as floods and water quality studies. Hydrologic models are analytical tools for studying several watershed problems, by simulating the hydrologic processes, under given conditions. It allows for wide experimentation.

Special studies, such as development of steep slopes, need extensive study of the regional geology, soil and hydrology among other factors.

The vast amount of watershed data necessitates practical classification systems (e.g., a grid based system compatible with a standard geographic grid system; e.g., Universal Transverse Mercator system). This assists in forming a geographic data base and is compatible with automated processing of remotely sensed data and brings it closer to a user-oriented, operational mode. Such a system provides a means of data acquisition, analysis, storage and retrieval of remotely sensed data.

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APPENDIXES

APPENDIX A

APPENDIX A

FORTRAN PROGRAMS

```
C THIS FORTRAN PROGRAM DRAWS 'GRIDS' OF VARIABLE SIZE
C PLOTTED ON IBM 1627 PLOTTER
COMMENT
      TYPE *,'INPUT XDIV,YDIV'
      ACCEPT *, XDIV,YDIV
      I1=XDIV+1.0
      I2=YDIV+1.0
      CALL PLOTKK
      CALL INITT(30)
      CALL VWINDO(0.,1.,0.,1.)
      DO 10 J=1,I1
      X=(J-1)/XDIV
      CALL MOVEA(X,0.0)
      CALL DRAWA(X,1.0)
10    CONTINUE
      DO 20 L=1,I2
      Y=(L-1)/YDIV
      CALL MOVEA(0.0,Y)
      CALL DRAWA(1.0,Y)
20    CONTINUE
      CALL FINITT(0,0)
      STOP
      END
```

```
C TABULATION OF 'SCS' CURVE NUMBER
C SUB-BASINS: UPSTREAM 'FAGAN CREEK' AND 'MOUNTAINBROOK'
C COMPUTATION OF 'MAXIMUM','MINIMUM' AND 'WEIGHTED AVERAGE' VALUES
      DIMENSION N(58)
      CALL ASSIGN (1,'SY:IN.DAT')
      CALL ASSIGN (2,'SY:O.FIN')
      READ (1,10) (N(I),I=1,58)
10    FORMAT (514)
      WRITE (2,15)
15    FORMAT (//,10X,' SCS CURVE NO: UPSTREAM FAGAN AND MOUNTAINBROOK')
      WRITE (2,20) (N(I),I=1,58)
20    FORMAT (//2X,10I5)
      DO 30 I=1,57
      DO 30 J=1,57
      L=N(J)
      K=J+1
      M=N(K)
      IF(L.LE.M) GO TO 30
      GO TO 40
40    N(J)=M
      N(K)=L
30    CONTINUE
      SUM=0.0
      K=0
      DO 60 I=1,58
      SUM=SUM+N(I)
      K=K+1
60    CONTINUE
      A=SUM/K
      WRITE (2,50)N(58),N(1),A
50    FORMAT (//,10X,'MAX',I5,//10X,'MIN',I5,//10X,'WT:AVERAGE',F5.1)
      STOP
      END
```

```
          SCS CURVE NO: UPSTREAM FAGAN AND MOUNTAINBROOK

   77   77   73   72   72   72   77   77   77   73

   72   72   72   77   77   77   77   77   73   72

   72   72   80   79   77   77   77   73   72   72

   82   86   77   77   77   73   72   75   77   77

   77   77   77   73   70   84   79   77   77   77

   70   82   77   77   77   77   77   75

          MAX   86

          MIN   70

          WT:AVERAGE 75.8
```

```
FORTRAN IV-PLUS V02-04F          12:55:01      20-SEP-79              PAGE 1
DP.FTN              /CK/TR:BLOCKS/WR

        C                          STRIP HYDROGRAPH MODEL
                  DOUBLE PRECISION Q(500),R(500),S(500),F(500),XLN(100),
                 1U(25),V(25),M(25),CTP(15),CAP,AP1,PERC,F3
                  CALL ASSIGN (5,'SY:IN.DAT')
                  CALL ASSIGN (6,'SY:OUT.FIN')
           10     FORMAT (5X,'ENTER LENGTH(M),SLOPE,MANNINGS N')
           20     FORMAT (F7.2,2F5.4)
           30     FORMAT (5X,'ENTER TIME STEP INCREMENT(SECS) AND # OF TIME STEPS')
           40     FORMAT (F4.0,I3)
           45     FORMAT (5X,'ENTER TOTAL TIME LIMIT(SECS)')
           46     FORMAT (I6)
           94     FORMAT (/////,2X,'TIME(SECS)',43X,'DISCHARGE(M3/SEC*10 -4)')
           95     FORMAT (/,7X,10(F5.2,5X),F5.2)
           205    FORMAT (5X,F9.2,5X,F15.10,5X,F15.10,5X,F15.10,5X,F15.10,5X,F15.10)
           50     FORMAT (5X,'ENTER # OF RAIN INCREMENTS')
           60     FORMAT (I3)
           70     FORMAT (5X,'ENTER RAIN RATE(M/SEC) AND DURATION(SECS)')
           80     FORMAT (5X,'TOTAL RUN TIME MUST BE ACCOUNTED FOR')
           90     FORMAT (F8.7,F5.0)
           91     FORMAT (2F6.4,2F11.9)
           92     FORMAT (5X,'0.',3X,'1',100A1)
           99     FORMAT ('1',/,10X,'# INDICATES RAINFALL',/,10X,'+ INDICATES
                 1INFILTRATION',/,10X,'* INDICATES DISCHARGE')
           101    FORMAT (5X,'ENTER SOIL MOISTURE CAPACITY(M);ANTECEDENT MOISTURE(M);
                 1PERC(M/SEC);FINAL INFILTRATION(M/SEC)')
           151    FORMAT (/////,6X,'TIME(SECS)',7X,'RAIN(M3/SEC)',7X,'INFIL(M3/SEC)'
                 1,11X,'H(M)',13X,'FLOW(M3/SEC)',10X,'CAP.(M)')
                  WRITE (6,10)
                  READ (5,20)XL,SL,EN
                  WRITE (6,30)
                  READ (5,40)D1,J
                  WRITE (6,45)
                  READ (5,46)N1
                  WRITE (6,50)
                  READ (5,60)J1
                  WRITE (6,101)
                  READ (5,91) CAP,AP1,PERC,F3
                  M(1)=0
                  WRITE (6,70)
                  WRITE (6,80)
                  DO 102 I=1,J1
           102    READ (5,90)V(I),U(I)
                  J2=J1+1
                  DO 111 I=2,J2
           111    M(I)=INT(U(I-1)/D1)+M(I-1)
                  DO 121 L=2,J2
                  L1=M(L-1)+1
                  L2=M(L)
                  DO 121 K1=L1,L2
           121    R(K1)=V(L-1)
                  M1=M(J2)
                  N=INT(N1/D1)
                  F5=(SL**.5/EN)
                  WRITE (6,151)
                  H=0.
                  SDELT=0.
```

```
FORTRAN IV-PLUS V02-04F          12:55:01     20-SEP-79              PAGE 2
DP.FTN                 /CK/TR:BLOCKS/WR

              K=0
              S(1)=CAP-API
              F3=F3*141732.
              DO 321 I=1,N
              K=K+1
              T=D1*I
              IF (H.LE.0.) GO TO 251
              IF (R(I).LE.0.) GO TO 231
        231   IF (S(I).LE.0.) GO TO 271
              S(I)=S(I)*39.37
              F(I)=(S(I))**1.4+F3
              F(I)=F(I)/141732.
              S(I)=S(I)/39.37
              H=H+(1.6*D1*(R(I)-(Q(I-1)/XL)-F(I)))
              IF (H.LE.0.) GO TO 281
        241   Q(I)=F5*.307*H**1.67
              GO TO 291
        251   IF (R(I).LE.0.) GO TO 255
              IF (S(I).LE.0.) GO TO 257
              S(I)=S(I)*39.37
              F(I)=(S(I))**1.4+F3
              S(I)=S(I)/39.37
              F(I)=F(I)/141732.
              IF (F(I).GT.R(I)) F(I)=R(I)
              H=1.6*D1*(R(I)-F(I))
        253   IF (H.LE.0.) GO TO 281
              Q(I)=F5*.307*H**1.67
              GO TO 291
        255   F(I)=0.
              H=0.
              Q(I)=0.
              GO TO 291
        257   S(I)=0.
              F(I)=PERC
              IF (F(I).GT.R(I)) F(I)=R(I)
              H=1.6*D1*(R(I)-F(I))
              GO TO 253
        271   S(I)=0.
              F(I)=PERC
              H=H+(1.6*D1*(R(I)-(Q(I-1)/XL)-F(I)))
              GO TO 253
        281   H=0.
              Q(I)=0.
        291   SDELT=(F(I)-PERC)*D1
              IF (SDELT.LE.(S(I)-CAP)) SDELT=S(I)-CAP
              S(I+1)=S(I)-SDELT
              IF (S(I+1).LT.0.) S(I+1)=0.
              IF (S(I+1).GT.CAP) S(I+1)=CAP
              IF (K.LT.J) GO TO 321
              WRITE (6,205) T,R(I),F(I),H,Q(I),S(I)
              K=0
        321   CONTINUE
              DATA STAR,BLANK,DOT,SLSH,PLUS,PND/'*',' ','.','I','+','#'/
        37    FORMAT (2X,F5.0,3X,A1,100A1)
              WRITE (6,36)
        36    FORMAT (/////,5X,'ENTER MAXIMUM DISCHARGE - XX.XX')
```

```
FORTRAN IV-PLUS V02-04F          12:55:01     20-SEP-79            PAGE 3
DP.FIN             /CK/TR:BLOCKS/WR

            READ (5,38) D
      38    FORMAT (F12.10)
            WRITE (6,39)
      39    FORMAT (5X,'ENTER TIME-SCALE STEP (SECS)')
            READ (5,60) I2
            IX=I2/D1
            WRITE (6,99)
            WRITE (6,94)
            H1=D*100.
            LM=0
            CTR(1)=0.
            TIME=0.
            D2=H1*10.
            DO 301 I=1,10
     301    CTR(I+1)=I*D2
            WRITE (6,95) (CTR(I),I=1,11)
            DO 308 J=1,100
     308    XLN(J)=DOT
            DO 309 I=10,100,10
     309    XLN(I)=SLSH
            WRITE (6,92) XLN
            DO 501 I=IX,N,IX
            TIME=TIME+I2
            F(I)=F(I)*XL
            R(I)=R(I)*XL
            G=SLSH
            J6=INT((F(I)*10000)/H1+.5)
            IF (J6.EQ.0) G=PLUS
            J5=INT((R(I)*10000.)/H1+.5)
            IF (J5.EQ.0) G=PND
            J8=INT((Q(I)*10000.)/H1+.5)
            IF (J8.EQ.0) G=STAR
            LM=LM+1
            IF (LM.EQ.5) GO TO 315
            DO 103 JK=1,100
     103    XLN(JK)=BLANK
     104    DO 105 JK=10,100,10
     105    XLN(JK)=SLSH
            IF (J6.EQ.0) GO TO 504
            XLN(J6)=PLUS
     504    IF (J5.EQ.0) GO TO 508
            XLN(J5)=PND
     508    IF (J8.EQ.0) GO TO 510
            XLN(J8)=STAR
     510    WRITE (6,37) TIME,G,XLN
            GO TO 501
     315    DO 109 JK=1,100
     109    XLN(JK)=DOT
            LM=0
            GO TO 104
     501    CONTINUE
            STOP
            END
```

APPENDIX B

APPENDIX B

STRIP HYDROGRAPH MODEL SAMPLE OUTPUTS

STRIP "A2"
Slope = 25%
Manning's "n" = 0.1

```
ENTER LENGTH(M),SLOPE,MANNINGS N
ENTER TIME STEP INCREMENT(SECS) AND # OF TIME STEPS
ENTER TOTAL TIME LIMIT(SECS)
ENTER # OF RAIN INCREMENTS
ENTER SOIL MOISTURE CAPACITY(M);ANTECEDENT MOISTURE(M)PERC(M/SEC);FINAL INFILTRATION(M/SEC)
ENTER RAIN RATE(M/SEC) AND DURATION(SECS)
TOTAL RUN TIME MUST BE ACCOUNTED FOR
```

TIME(SECS)	RAIN(M3/SEC)	INFIL(M3/SEC)	h(M)	FLOW(M3/SEC)	CAP.(M)
100.00	0.0000020000	0.0000150000	0.0007994247	0.0000103216	0.0000000000
200.00	0.0000020000	0.0000150000	0.0015960758	0.0000327497	0.0000000000
300.00	0.0000020000	0.0000150000	0.0023861749	0.0000641917	0.0000000000
400.00	0.0000020000	0.0000150000	0.0031742977	0.0001032429	0.0000000000
500.00	0.0000020000	0.0000150000	0.0039532224	0.0001489420	0.0000000000
600.00	0.0000020000	0.0000150000	0.0047238721	0.0002005332	0.0000000000
700.00	0.0000020000	0.0000150000	0.0054852907	0.0002573783	0.0000000000
800.00	0.0000020000	0.0000150000	0.0062366235	0.0003189144	0.0000000000
900.00	0.0000020000	0.0000150000	0.0069771083	0.0003846328	0.0000000000
1000.00	0.0000020000	0.0000150000	0.0077060671	0.0004540661	0.0000000000
1100.00	0.0000020000	0.0000150000	0.0055637271	0.0002635540	0.0000000000
1200.00	0.0000020000	0.0000150000	0.0034504887	0.0001186777	0.0000000000
1300.00	0.0000020000	0.0000150000	0.0013582000	0.0000250126	0.0000000000
1400.00	0.0000020000	0.0000150000	0.0000000000	0.0000000000	0.0002600000
1500.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0015600000
1600.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0028600000
1700.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0041600000
1800.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0054600000
1900.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0067600000
2000.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0080600000

Peak discharge = 0.0004540661 m^3/s
Duration of run = 2000 seconds

```
ENTER MAXIMUM DISCHARGE - XX.XX
ENTER TIME-SCALE STEP (SECS)
```

STRIP "A2"
Slope = 35%
Manning's "n" = 0.1

```
ENTER LENGTH(M),SLOPE,MANNINGS N
ENTER TIME STEP INCREMENT(SECS) AND # OF TIME STEPS
ENTER TOTAL TIME LIMIT(SECS)
ENTER # OF RAIN INCREMENTS
ENTER SOIL MOISTURE CAPACITY(M);ANTECEDENT MOISTURE(M)PERC(M/SEC);FINAL INFILTRATION(M/SEC)
ENTER RAIN RATE(M/SEC) AND DURATION(SECS)
TOTAL RUN TIME MUST BE ACCOUNTED FOR
```

TIME(SECS)	RAIN(M3/SEC)	INFIL(M3/SEC)	H(M)	FLOW(M3/SEC)	CAP.(M)
100.00	0.0000200000	0.0000150000	0.0007993194	0.0000122100	0.0000000000
200.00	0.0000200000	0.0000150000	0.0015953589	0.0000387209	0.0000000000
300.00	0.0000200000	0.0000150000	0.0023860203	0.0000758382	0.0000000000
400.00	0.0000200000	0.0000150000	0.0031696325	0.0001216590	0.0000000000
500.00	0.0000200000	0.0000150000	0.0039447700	0.0001758017	0.0000000000
600.00	0.0000200000	0.0000150000	0.0047101867	0.0002361272	0.0000000000
700.00	0.0000200000	0.0000150000	0.0054647862	0.0003026355	0.0000000000
800.00	0.0000200000	0.0000150000	0.0062076021	0.0003744166	0.0000000000
900.00	0.0000200000	0.0000150000	0.0069377827	0.0004508279	0.0000000000
1000.00	0.0000200000	0.0000150000	0.0076545826	0.0005312776	0.0000000000
1100.00	0.0000200000	0.0000150000	0.0055018454	0.0003060706	0.0000000000
1200.00	0.0000200000	0.0000150000	0.0033834204	0.0001358930	0.0000000000
1300.00	0.0000200000	0.0000150000	0.0012695078	0.0000271382	0.0000000000
1400.00	0.0000200000	0.0000150000	0.0000000000	0.0000000000	0.0000000000
1500.00	0.0000200000	0.0000200000	0.0000000000	0.0000000000	0.0002600000
1600.00	0.0000200000	0.0000200000	0.0000000000	0.0000000000	0.0015600000
1700.00	0.0000200000	0.0000200000	0.0000000000	0.0000000000	0.0028600000
1800.00	0.0000200000	0.0000200000	0.0000000000	0.0000000000	0.0041600000
1900.00	0.0000200000	0.0000200000	0.0000000000	0.0000000000	0.0054600000
2000.00	0.0000200000	0.0000200000	0.0000000000	0.0000000000	0.0067600000
					0.0080600000

```
ENTER MAXIMUM DISCHARGE - XX.XX
ENTER TIME-SCALE STEP (SECS)
```

Peak discharge = 0.0005312776 m^3/s
Duration of run = 2000 seconds

STRIP "A2"
Slope = 25%
Manning's "n" = 0.08

```
ENTER LENGTH(M),SLOPE,MANNINGS N
ENTER TIME STEP INCREMENT(SECS) AND # OF TIME STEPS
ENTER TOTAL TIME LIMIT(SECS)
ENTER # OF RAIN INCREMENTS
ENTER SOIL MOISTURE CAPACITY(M);ANTECEDENT MOISTURE(M)PERC(M/SEC);FINAL INFILTRATION(M/SEC)
ENTER RAIN RATE(M/SEC) AND DURATION(SECS)
TOTAL RUN TIME MUST BE ACCOUNTED FOR
```

TIME(SECS)	RAIN(M3/SEC)	INFIL(M3/SEC)	H(M)	FLOW(M3/SEC)	CAP.(M)
100.00	0.0000200000	0.0000150000	0.0007992810	0.0000128961	0.0000000000
200.00	0.0000200000	0.0000150000	0.0015950975	0.0000406953	0.0000000000
300.00	0.0000200000	0.0000150000	0.0023852361	0.0000800748	0.0000000000
400.00	0.0000200000	0.0000150000	0.0031679359	0.0001286770	0.0000000000
500.00	0.0000200000	0.0000150000	0.0039416980	0.0001852720	0.0000000000
600.00	0.0000200000	0.0000150000	0.0047052181	0.0002490156	0.0000000000
700.00	0.0000200000	0.0000150000	0.0054573510	0.0003189910	0.0000000000
800.00	0.0000200000	0.0000150000	0.0061970921	0.0003944325	0.0000000000
900.00	0.0000200000	0.0000150000	0.0069235601	0.0004746447	0.0000000000
1000.00	0.0000200000	0.0000150000	0.0076359902	0.0005589893	0.0000000000
1100.00	0.0000020000	0.0000150000	0.0054795356	0.0003211592	0.0000000000
1200.00	0.0000020000	0.0000150000	0.0033592829	0.0001418568	0.0000000000
1300.00	0.0000020000	0.0000150000	0.0012648199	0.0000277592	0.0000000000
1400.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0002600000
1500.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0015600000
1600.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0028600000
1700.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0041600000
1800.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0054600000
1900.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0067600000
2000.00	0.0000020000	0.0000020000	0.0000000000	0.0000000000	0.0080600000

```
ENTER MAXIMUM DISCHARGE - XX.XX
ENTER TIME-SCALE STEP (SECS)
```

Peak discharge = 0.0005589893 m^3/s
Duration of run = 2000 seconds

STRIP "C"

Slope = 12%

Manning's "n" = 0.028

```
ENTER LENGTH(M),SLOPE,MANNINGS N
ENTER TIME STEP INCREMENT(SECS) AND # OF TIME STEPS
ENTER TOTAL TIME LIMIT(SECS)
ENTER # OF RAIN INCREMENTS
ENTER SOIL MOISTURE CAPACITY(M);ANTECEDENT MOISTURE(M)PERC(M/SEC);FINAL INFILTRATION(M/SEC)
ENTER RAIN RATE(M/SEC) AND DURATION(SECS)
TOTAL RUN TIME MUST BE ACCOUNTED FOR
```

TIME(SECS)	RAIN(M3/SEC)	INFIL(M3/SEC)	H(M)	FLOW(M3/SEC)	CAP.(M)
100.00	0.0000020000	0.0000011000	0.0030026066	0.0002326315	0.0000000000
200.00	0.0000020000	0.0000011000	0.0059055900	0.0007204118	0.0000000000
300.00	0.0000020000	0.0000011000	0.0086519131	0.0013631652	0.0000000000
400.00	0.0000020000	0.0000011000	0.0112067293	0.0020999096	0.0000000000
500.00	0.0000020000	0.0000011000	0.0135500876	0.0028834643	0.0000000000
600.00	0.0000020000	0.0000011000	0.0156737957	0.0036771551	0.0000000000
700.00	0.0000020000	0.0000011000	0.0175766706	0.0044531612	0.0000000000
800.00	0.0000020000	0.0000011000	0.0192721598	0.0051928377	0.0000000000
900.00	0.0000020000	0.0000011000	0.0207662564	0.0058824634	0.0000000000
1000.00	0.0000020000	0.0000011000	0.0220758151	0.0065149614	0.0000000000
1100.00	0.0000020000	0.0000011000	0.0205075797	0.0057606050	0.0000000000
1200.00	0.0000020000	0.0000011000	0.0191327333	0.0051302523	0.0000000000
1300.00	0.0000020000	0.0000011000	0.0179201141	0.0045986602	0.0000000000
1400.00	0.0000020000	0.0000011000	0.0168447439	0.0041473093	0.0000000000
1500.00	0.0000020000	0.0000011000	0.0158863736	0.0037608200	0.0000000000
1600.00	0.0000020000	0.0000011000	0.0150284423	0.0034278156	0.0000000000
1700.00	0.0000020000	0.0000011000	0.0142572602	0.0031391513	0.0000000000
1800.00	0.0000020000	0.0000011000	0.0135615226	0.0028875289	0.0000000000
1900.00	0.0000020000	0.0000011000	0.0129316456	0.0026670613	0.0000000000
2000.00	0.0000020000	0.0000011000	0.0123590136	0.0024729725	0.0000000000

```
ENTER MAXIMUM DISCHARGE - XX.XX
ENTER TIME-SCALE STEP (SECS)
```

Peak discharge = 0.0065149614 m^3/s

Duration of run = 2000 seconds

STRIP "D"

Slope = 16%

Manning's "n" = 0.038

ENTER LENGTH(M),SLOPE,MANNINGS N
ENTER TIME STEP INCREMENT(SECS) AND # OF TIME STEPS
ENTER TOTAL TIME LIMIT(SECS)
ENTER # OF RAIN INCREMENTS
ENTER SOIL MOISTURE CAPACITY(M);ANTECEDENT MOISTURE(M)PERC(M/SEC);FINAL INFILTRATION(M/SEC)
ENTER RAIN RATE(M/SEC) AND DURATION(SECS)
TOTAL RUN TIME MUST BE ACCOUNTED FOR

TIME(SECS)	RAIN(M3/SEC)	INFIL(M3/SEC)	D(M)	FLOW(M3/SEC)	CAP.(M)
100.00	0.0000020000	0.0000011000	0.0030119461	0.0001941083	0.0000000000
200.00	0.0000020000	0.0000011000	0.0059664203	0.0006235295	0.0000000000
300.00	0.0000020000	0.0000011000	0.0088268998	0.0011997174	0.0000000000
400.00	0.0000020000	0.0000011000	0.0115749678	0.0018857685	0.0000000000
500.00	0.0000020000	0.0000011000	0.0141871041	0.0026489710	0.0000000000
600.00	0.0000020000	0.0000011000	0.0166533757	0.0034619726	0.0000000000
700.00	0.0000020000	0.0000011000	0.0189665332	0.0043016451	0.0000000000
800.00	0.0000020000	0.0000011000	0.0211232491	0.0051495014	0.0000000000
900.00	0.0000020000	0.0000011000	0.0231234264	0.0059893811	0.0000000000
1000.00	0.0000020000	0.0000011000	0.0249695797	0.0068091308	0.0000000000
1100.00	0.0000020000	0.0000011000	0.0238936990	0.0063262768	0.0000000000
1200.00	0.0000020000	0.0000011000	0.0229026892	0.0058942926	0.0000000000
1300.00	0.0000020000	0.0000011000	0.0219883025	0.0055064904	0.0000000000
1400.00	0.0000020000	0.0000011000	0.0211422369	0.0051572346	0.0000000000
1500.00	0.0000020000	0.0000011000	0.0203579664	0.0048417393	0.0000000000
1600.00	0.0000020000	0.0000011000	0.0196295902	0.0045559248	0.0000000000
1700.00	0.0000020000	0.0000011000	0.0189519152	0.0042963064	0.0000000000
1800.00	0.0000020000	0.0000011000	0.0183203369	0.0040598852	0.0000000000
1900.00	0.0000020000	0.0000011000	0.0177307855	0.0038440610	0.0000000000
2000.00	0.0000020000	0.0000011000	0.0171796419	0.0036466036	0.0000000000

ENTER MAXIMUM DISCHARGE - XX.XX
ENTER TIME-SCALE STEP (SECS)

Peak discharge = 0.0068091308 m^3/s

Duration of run = 2000 seconds

STRIP "D"

Slope = 16%

Manning's "n" = 0.04

```
ENTER LENGTH(M),SLOPE,MANNINGS N
ENTER TIME STEP INCREMENT(SECS) AND # OF TIME STEPS
ENTER TOTAL TIME LIMIT(SECS)
ENTER # OF RAIN INCREMENTS
ENTER SOIL MOISTURE CAPACITY(M);ANTECEDENT MOISTURE(M)PERC(M/SEC);FINAL INFILTRATION(M/SEC)
ENTER RAIN RATE(M/SEC) AND DURATION(SECS)
TOTAL RUN TIME MUST BE ACCOUNTED FOR
```

TIME(SECS)	RAIN(M3/SEC)	INFIL(M3/SEC)	H(M)	FLOW(M3/SEC)	CAP.(M)
100.00	0.0000020000	0.0000011000	0.0030125468	0.0001892161	0.0000000000
200.00	0.0000020000	0.0000011000	0.0059704487	0.0005930212	0.0000000000
300.00	0.0000020000	0.0000011000	0.0088407490	0.0011422870	0.0000000000
400.00	0.0000020000	0.0000011000	0.0115999505	0.0017979604	0.0000000000
500.00	0.0000020000	0.0000011000	0.0142309633	0.0025295359	0.0000000000
600.00	0.0000020000	0.0000011000	0.0167219825	0.0033115330	0.0000000000
700.00	0.0000020000	0.0000011000	0.0190654546	0.0041224114	0.0000000000
800.00	0.0000020000	0.0000011000	0.0212576166	0.0049441061	0.0000000000
900.00	0.0000020000	0.0000011000	0.0232977439	0.0057617258	0.0000000000
1000.00	0.0000020000	0.0000011000	0.0251876339	0.0065632858	0.0000000000
1100.00	0.0000020000	0.0000011000	0.0241539067	0.0061196620	0.0000000000
1200.00	0.0000020000	0.0000011000	0.0231985170	0.0057208035	0.0000000000
1300.00	0.0000020000	0.0000011000	0.0223136451	0.0053610676	0.0000000000
1400.00	0.0000020000	0.0000011000	0.0214924676	0.0050350588	0.0000000000
1500.00	0.0000020000	0.0000011000	0.0207289062	0.0047404882	0.0000000000
1600.00	0.0000020000	0.0000011000	0.0200178530	0.0044720406	0.0000000000
1700.00	0.0000020000	0.0000011000	0.0193544347	0.0042272885	0.0000000000
1800.00	0.0000020000	0.0000011000	0.0187345464	0.0040036184	0.0000000000
1900.00	0.0000020000	0.0000011000	0.0181544777	0.0037987556	0.0000000000
2000.00	0.0000020000	0.0000011000	0.0176109187	0.0036107264	0.0000000000

Peak discharge = 0.0065632858 m^3/s

Duration of run = 2000 seconds

```
ENTER MAXIMUM DISCHARGE - XX.XX
ENTER TIME-SCALE STEP (SECS)
```

STRIP "A2"
Slope = 25%
Manning's "n" = 0.1

Soil Moisture Capacity = 0.0640 meter
Antecedent Moisture = 0.2300 meter
Percolation = 0.000001600 m/s
Final Infiltration = 0.000002778 m/s

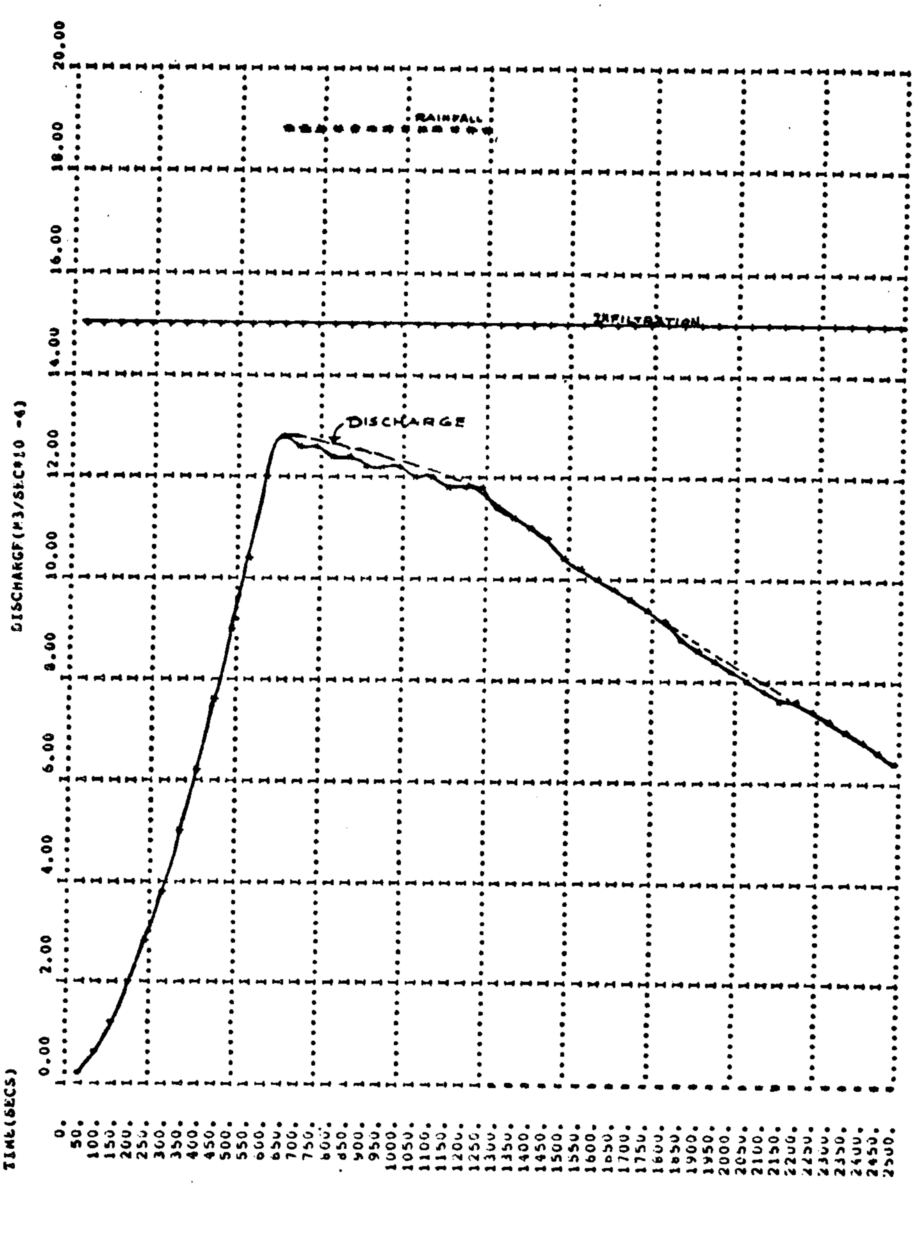
```
ENTER LENGTH(M),SLOPE,MANNINGS N
ENTER TIME STEP INCREMENT(SECS) AND # OF TIME STEPS
ENTER TOTAL TIME LIMIT(SECS)
ENTER # OF RAIN INCREMENTS
ENTER SOIL MOISTURE CAPACITY(M);ANTECEDENT MOISTURE(M)PERC(M/SEC);FINAL INFILTRATION(M/SEC)
ENTER RAIN RATE(M/SEC) AND DURATION(SECS)
TOTAL RUN TIME MUST BE ACCOUNTED FOR
```

TIME(SECS)	RAIN(M3/SEC)	INFIL(M3/SEC)	H(M)	FLOW(M3/SEC)	CAP.(M)
400.00	0.0000200000	0.0000016000	0.0115593635	0.0006937336	0.0000000000
800.00	0.0000020000	0.0000016000	0.0136772083	0.0012126995	0.0000000000
1200.00	0.0000000000	0.0000016000	0.0127038984	0.0010463658	0.0000000000
1600.00	0.0000000000	0.0000016000	0.0110378396	0.0008274179	0.0000000000
2000.00	0.0000000000	0.0000016000	0.0095091691	0.0006450719	0.0000000000

```
ENTER MAXIMUM DISCHARGE - XX.XX
ENTER TIME-SCALE STEP (SECS)
```

Sample Graphical Output

INDICATES RAINFALL
INDICATES INFILTRATION
INDICATES DISCHARGE



VITA

Vijay Kumar Srinivas was born on March 15, 1948 in Bangalore, India. He graduated in 1964 from St. Joseph's High School in Bangalore, India. In June 1966 he entered the University of Kerala, Trivandrum, India, and received the degree of Bachelor of Science in Physics in 1969, and the degree of Bachelor of Science in Electronics and Communication Engineering in 1974.

During the period November 1974 to April 1975, he worked as a research assistant in the Electronics Laboratory at the Indian Scientific Satellite Project (ISSP) at Bangalore, India.

In December 1975, he joined the staff of Ecosystems International, Inc., Gambrills, Maryland, U.S.A. and was involved in several State, Federal and Foreign contract projects in the area of the Applications of Remote Sensing Technology.

In the fall of 1977 he accepted a research assistantship at The University of Tennessee Space Institute, Remote Sensing Division, and began study towards a Master's degree in Engineering Science, which was awarded in December 1979.

The author is a member of the American Society of Photogrammetry and Remote Sensing.