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OVERLAND FLOW MODELLING

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ABSTRACT

Surface flow estimation is needed by planners and managers of water resource system. Most of the analysis are based on linear systems, wherein the watershed is assumed to be virgin. But, naturally, the watershed changes considerably due to man made activities like deforestation, urbanisation, etc. These do not permit application of a linear model like unit hydrograph. Moreover, precise information on spatial and temporal distribution of flow are needed for water quality studies. Distributed models are used in such situations. These are physically based models gradually varied unsteady flow equations by numerical techniques. Literature survey revealed that finite difference, finite element and method of characteristics are comonly used. Infiltration component is one of the important aspect of overland flow computations. Antecedent moisture content needs to be estimated accurately for the model to be realistic.

In many distributed models, the watershed is discretized into several sub-watersheds and assumed to comprise of plane surface flow and channel flow before reaching the outlet. The heterogenity of the watershed poses a major problem in averaging the properties of the sub-watersheds. The effect of averaging and how small the sub-watershed should be (for better results) is not known at present.

A distributed model using method of characteristics and a concept of homogeneous response units was prepared. A watershed used by Ross and others in 1978 for testing their model was choosed for the application of the present model, considering the availability of data necessary for the model.

Results showed good performance of the model. The computed hydrograph nearly matches that of Ross and others.

1.0 INTRODUCTION

There is an increasing awareness of the temporal and spacial distribution of water as the population grows, especially for flood control purposes. In addition to the water quantity, the quality of water, soil erosion and sediment transport also assume an important role in the hydrological problems. There are a number of hydrologic simulation models based on crude simplifications of the inherent heteorogeneties and temporal non-stationorities. Therefore, these models are inappropriate for solution of the needed hydrologic problems. In recent years, the hydrological research has improved the physical understanding, through improved data collection. This coupled with the availability of high speed computers brought up numerical models. Various available models are discussed together with a brief introduction specifying the physical problems.

Portions of precipitation striking the ground take different path of travel. Part of the storm precipitation is intercepted by vegetationand other forms of land cover. Precipitation intercepted by vegetation may be retained on leaves or blades of grass before getting evaporated. Partly this interception reaches the ground as through fall. This and the portion of the precipitation directly falling on the bare land after meeting the infiltration and depression storage requirements form overland flow.

Firstly they flow over surfaces and enter the channels. These channels join to a stream. The overland flow observed at the streams is normally of interest to designers and planners of water resource projects.

Hydrologic forecasts are used for issue of flood warnings, rational regulation of runoff, etc. Most of the methods of analysis are made on the linear models like unit hydrographs. These models assume a virgin watershed, i.e. the characteristics of the watershed do not change with time. But in reality, due to increased human activities on the watershed, the land use pattern changes from time to time. The cultivation practices soil conservation practices affect the response of the watershed to rain. This needed physically based models for runoff computations. Another reason for more complex model stems from the great concern on water quality. New trends in the use of 'on line operation' with observation-transmission-processing-and regulation demand the increase of the capabilities of the runoff models.

The advent of high speed electronic computers and the improvement in numerical techniques have brought a number of models. However, many of them are in a research stage.

The models can be classed into several groups. Some of them are given below :

I. (i) Lumped model
   (ii) Distributed model

II. (i) Models capable of simulating human interference in the behaviour of a basin
   (ii) Models considering virgin basin only

III. (i) Linear models
     (ii) Non-linear models

IV. (i) Finite difference models
     (ii) Finite element models
     (iii) Models using method of characteristics

V. (i) Kinematic models
     (ii) Dynamic models

Horton was the first to investigate overland flow on experimental plot for soil erosion studies in 1938. Later, several researchers have worked on modellingoverland flow using gradually varied unsteady flow equation. It is usual to assume the watershed to comprise of planes and channel network, i.e. planes which directly discharge to channel in the form of lateral flow. In nature, the flow contribution to the channels takes place at definite locations defined by the topography. In fact, the mesoscale features of rills contribute to tiny creeks and they in turn joins streams of first order. Successively, stream order increases to the dimension of the channel normally considered in the model. These features and the surface roughness can not be measured easily and hence lumped into the parameters defining the model (usually roughness coefficient).

Besides a brief review, development and application of a specific model are described in this report.

2.0 REVIEW

2.1 Physical Problem

The precipitation over a catchment occurs wetting vegetation, bare drock, debris, and soil surface. It may directly fall on to a water body too. In its transit, water (or moisture) may be stored on the vegetation leaf and stem surfaces as interception storage beforeit evaporates or reaches the ground. While evaporation is a continuous process (of varying rate), the water is drained under gravity as surface and sub-surface drainage to the outlet of the catchment. On the surface of the catchment there exist a detention/depression storage causing a delayed runoff and increasing evaporation. On a totally impermeable surface the excess precipitation after filling the small depressions begins to appear as over land flow. In the case of permeable area the water can penetrate into the soil. The rate at which water can travel through the soil causing infiltration depends on the soil characteristics and the moisture content within. The quantity of water penetrated from the precipitation depends on the rainfall intensity.

A balance between precipitation 'P' evaporation 'E' infiltration, 'I' overland flow 'F' and the change in storage of water ΔS can be written as follows:

$$P = E + I + F + \Delta S \qquad (1)$$

The ΔS include changes in canopy storage, detention/depression storage.

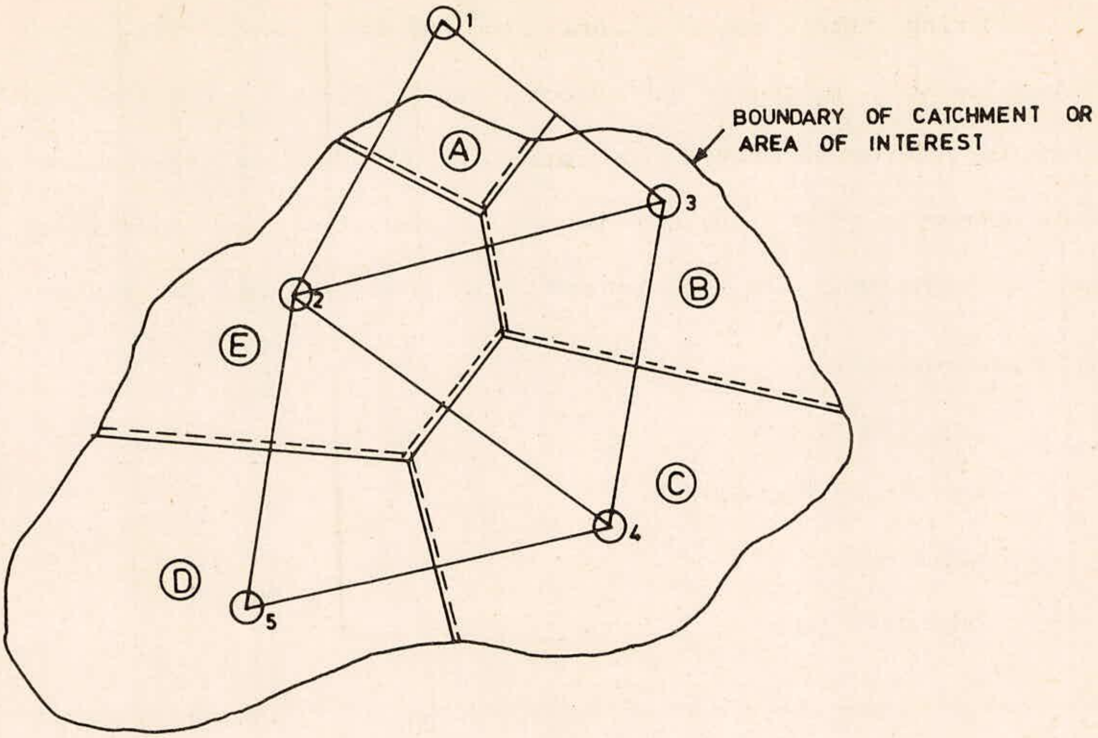


Figure 1 : Catchment showing the raingauges

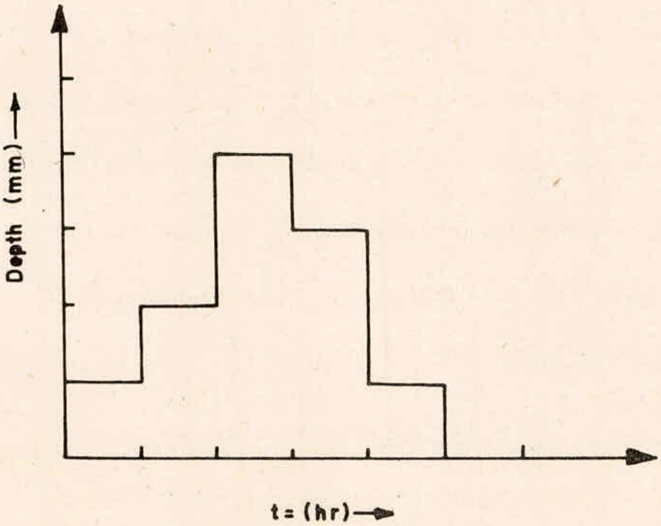


Figure 2 : Hyetograph

During this period plants also consume water and cause changes in soil moisture and evaporation. Normally the combined effect is studied as evapotranspiration. For the study of overland flow, however, this process is not important. The identified physical components for an overland flow modelling are as follows:

1. Precipitation
2. Canopy storage
3. Depression storage
4. Infiltration
5. Catchment flow

Each one of these are briefly described in the following sections

2.1.1 Rainfall

Rainfall is the deposition of water from the atmosphere, (precipitation in the form of rain is only dealt in overland flow modelling hence the term rainfall will be used) in the form of water drops. Different sizes of drops are present in a rainspell. The amount of rainfall per unit time varies from location to location and time to time also. An assesment of rainfall over a catchment is made from the basic information provided by the raingauges situated in and around the catchment as shown in Fig.1.

Out of the five gauge one is situated out side the boundary, but provide information about the rainfall over the catchment. The area marked A, B, C, D and E (obtained by Thiessen polygon method) can be said to have experienced the rainfall recorded in the raingauges 1,2,3,4 and 5 respectively. The spacial distribution within each influencing area (A, B, C, D, E) is assumed to be uniform and the temporal variation as given by the recorded rainfall of the respective gauges is assumed to have occured over each of them. For example the hyetograph shown in Fig.2 is assumed to have occured over the area B uniformly in space.

2.1.2 Canopy storage

Rainfall caught by the vegetative canopy goes into storage first and partly finds its way down to the ground. Drops stricking to the leaves are mostly retained. The volume of water retained depends on: (1) the position of the leaf (horizontal or vertical or inclined), (2) surface tension relation between the leaf and water, (3) wind velocity, (4) intensity of rainfall, (5) drop size and drop velocity of the falling rain, and (6) stage of the crop. When the maximum storage is reached drops begin to form at the edges of the leaves and eventually fall either to the lower leaf or over the ground beneath them. By the impact of falling rain or by the wind these leaves might get shaken and throw more rain drops from their surface. The wind reduces the canopy storage which is normally lost as evaporation after the rainfall. But the presence of wind cause evaporation loss more. Thus wind has both negative and positive effect on water balance. Lull (1964) states that grasses and herbs covered area intercept large amount of rainfall since their leaf area to ground area ratio approaches that of forest vegetation. One square metre of big bluestem had a total of 6 square meters including both sides of the leaves.

Coniferous trees intercept more than decidous trees. The interception by coniferous trees may be 25 to 30% of the rain. Only 5% of it finds its way down to the ground.

Canopy storage of the watershed are greatly affected by man made activity like deforestation etc.

2.1.3 Depression storage

Before the flow on the catchment surface begins the depressions are filled by the rain. The depression storage has to be estimated. The storage is greatly affected by agricultural practices. Ploughing reduces this storage except in case of contour ploughing where water can be stored in the furrows.

2.1.4. Infiltration

Infiltration is defined as the passage of water through the ground surface into the soil. Several techniques for modelling infiltration are available to the catchment modeller.

The rate of infiltration is normally very high at the begining and diminishes during rainfall toward a constant rate. Infiltration affects runoff as could be seen from the runoff of a permeable and impermeable areas. Infiltration changes the moisture content in soil and is affected by transpiration of plants and the evaporation of soil moisture (Mus Grave et al, 1964). Infiltration is considered to have three step sequence in the above reference, viz. (1) surface entry, (2) transmission through the soil, and (3) depletion of storage capacity in the soil.

Infiltration indices are average infiltration rates. The usage of these for runoff computations contains the error of small infiltration at the begining and larger infiltration at the end of the rainfall. As a consequence, the analysis produce an early flood peak and the hydrograph might also be much different from the observed one. The index, w index are some of the commonly used methods under this category.

In 1930's the Kostiakov and Horton equations for infiltration were used. These equations (Childs, 1969) were popular because of their simplicity. However, they could not gain popularity owing to the difficulty of estimating the necessary parameters. The Philip (1957) and Holton (1961) equations are also in use. Holton (1961) is the result of fitting of an assumed relationship between infiltration rates, infiltrated volume and soil capacity to a very large number of results obtained with field infiltrometers. Since this equation has infiltrated volume as its independent parameter it can be used for rainfall infiltration at the rates less than the infiltration capacity. However, the problem with this equation lies in determining the working depth and hence the storage of the soil.

At the University of Melbourne, application of Darcy's law to infiltration under ponding conditions was made in 1911. Philip in 1954 independently derived the same equation. Later a reviewer discovered Philip's works was similar to that of Green and Ampt done in 1911. Thereafter the Green and Ampt equation received a renewed attention.

Green and Ampt model is a 'piston-flow model' in which water displaces the air in the voids of the soil as the wetting front move downwards, with an assumption that the wetting front is sharply defined in the soil which is not true in all cases. Further works on this can be seen in Bouwer (1969), Morel Seytoux et al (1974), and in Mein and Larson (1971). However the Green and Ampt formulation is more difficult than Horton since the former is implicit with respect to time as per Li, et al (1979), who prepared explicit formulation of the equation.

Boughton (1975) model used Horton equation to relate infiltration and soil store content. In the Sacramento model on equation prepared by Burnash, Ferral and McGuire (1973) (as given below) is used:

$$\Delta I = C\ [1 + B\ (USMAX - US)/USMAX)^{n}] \qquad \dots (2)$$

where,

B, n are parameters

ΔI is the infiltration capacity (L^3/T)

US is the stored water (L^3)

USMAX is the maximum volume of storage (L^3)

C the infiltration capacity at US = USMAX

Papadakis (1973) suggested flooding type infiltrometer tests to determine the Horton's infiltration parameters for a given soil and for Antecedent precipitation index.

2.1.5 Surface flow

The rain water in excess of canopy storage, depression storage, infiltration undergoes a free surface flow. Water drops gathered at a location are determined by the geometry of the small area within the catchment and the intensity of special characteristics of the rainfall. They form tiny tracks leading to a well defined creek. These creeks can be assumed to receive water at numerous locations justifying a continuous lateral flow in space as shown in figure 3.

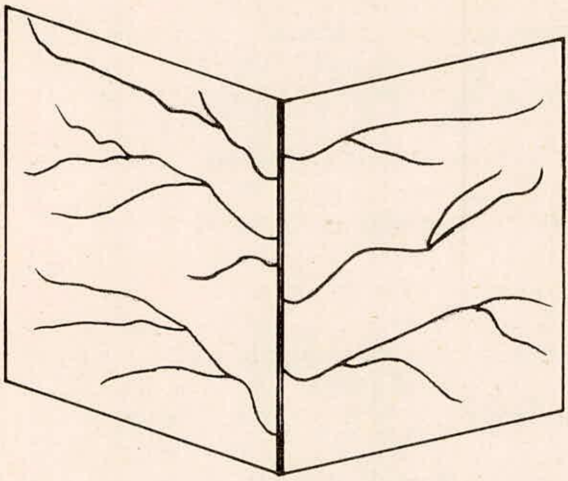


Figure 3 : Creek and tiny tracks draining a surface

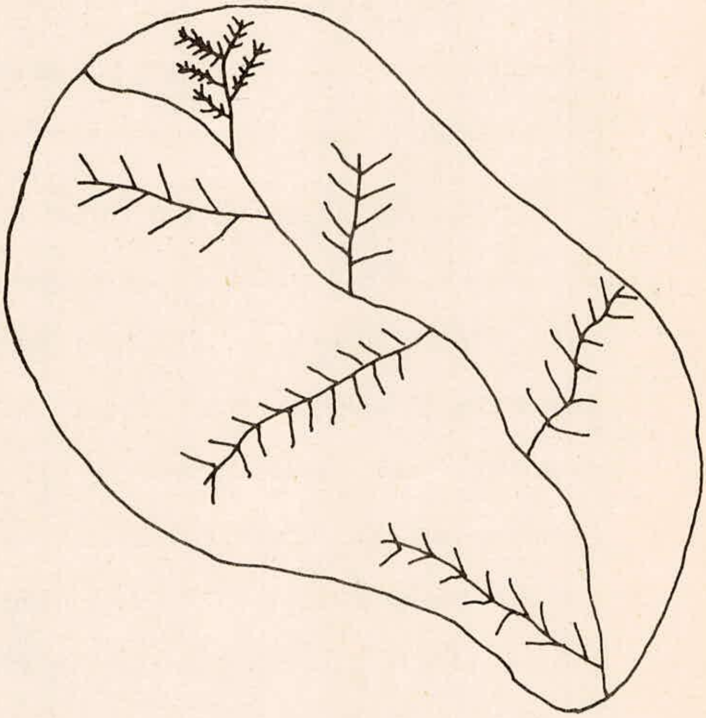


Figure 4 : Stream network

These creeks discharge at finite locations to the streams of various order. The streams in turn contribute to the streams of higher order streams. The figure 4 shows a schematic diagram of this network.

The flow from the catchment at G is of interest, for the purpose of flood control.

Varying degrees of approximation are made to compute the catchment flow/overland flow which is the quick response of the catchment to rain.

Sherman (1932) used linear system theory known as unit hydrograph methods to get the stream flow. Zoch (1934-37) assumed that the discharge is proportional to the amount of rain water remaining on the soil at that time. In :ther words he assumed a storage (linear reservoir) in the soil, Whereas Clark (1945) assumed a storage in the channel and presented a time area concentration curve.

Kelley (1955) found that in many practical cases smoothing was sufficient replacing time area curve by an isoscles triangle. Nash (1957) suggested a series of successive linear reservoirs of equal delay time to route the rainfall. Dooge (1959) placed linear reservoir and linear channels in series. Retaining many of the features of the linear models, the quasi linear models were developed as for example Diskin (1972), Singh (1964), Kulandaiswamy (19). Prasad (1967) proposed non-linear storage model. While the efforts on these simplified models continued, attempts for distributed models solving continuity and momentum equations were also made; for example as in SHE Model Roll et al finite element model. Numerous urban runoff digital models for simulating this part of hydrologic cycle were developed in USA. A list of simulation models can be seen in Viessman et al (1977). Some of the models are briefly given in the section 2.3.

2.2 General Structure of a Distributed Model

The components identified in section 2.1, except for the catchment flow are estimated either by measurements or by analytical expressions. In some cases infiltration was also modelled numerically. The catchment flow is described by the continuity and mementum equations as follows:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = r \qquad \ldots (3)$$

$$\frac{\partial q}{\partial t} + \frac{q}{y}\frac{\partial q}{\partial x} + gy\ (S_f - S_o + \frac{\partial y}{\partial x}) = 0 \qquad \ldots (4)$$

where,

q is discharge per unit width of the flowing section

y is the depth of flow

r is the rainfall or lateral flow

S_f is energy slope

S_o is slope of the bed

In the case of plain surface rain forms the lateral flow and in the case of channel the routed flow of the plane surface forms the lateral flow.

At the upstream end of the plane surface or the channel the dependent variable, here the depth of the flow is specified for all the time of numerical simulation.

The depth of flow at all the locations of computation are specified initially i.e. at the beginning of computation. The downstream condition may be assumed to be uniform flow at away from the influence of the incident hydrograph/hyetograph.

The energy slope is usually determined by the Manning's equation:

$$q = \frac{1}{n} y^{5/3} \quad S_o^{1/2} \qquad \ldots (5)$$

for a wide channel, or

$$q = \frac{1}{n} y \, R^{2/3} \, S_o^{1/2} \qquad \ldots (6)$$

where, n is Manning's coefficient

R is hydraulic depth

S_o, q, y are as defined earlier

Since these partial differential equations form a system of non-linear simultaneous equations, they are solved by numerical techniques. A review of hydraulic routing techniques can be seen in Palaniappan (1985).

The finite difference, finite element methods and method of characteristics are commonly used methods. A description of these methods can be seen in Mahmood et al (1975). The method of characteristics used in this study is described in Appendix I. A comparison of finite element methods and finite difference methods is given in Appendix II.

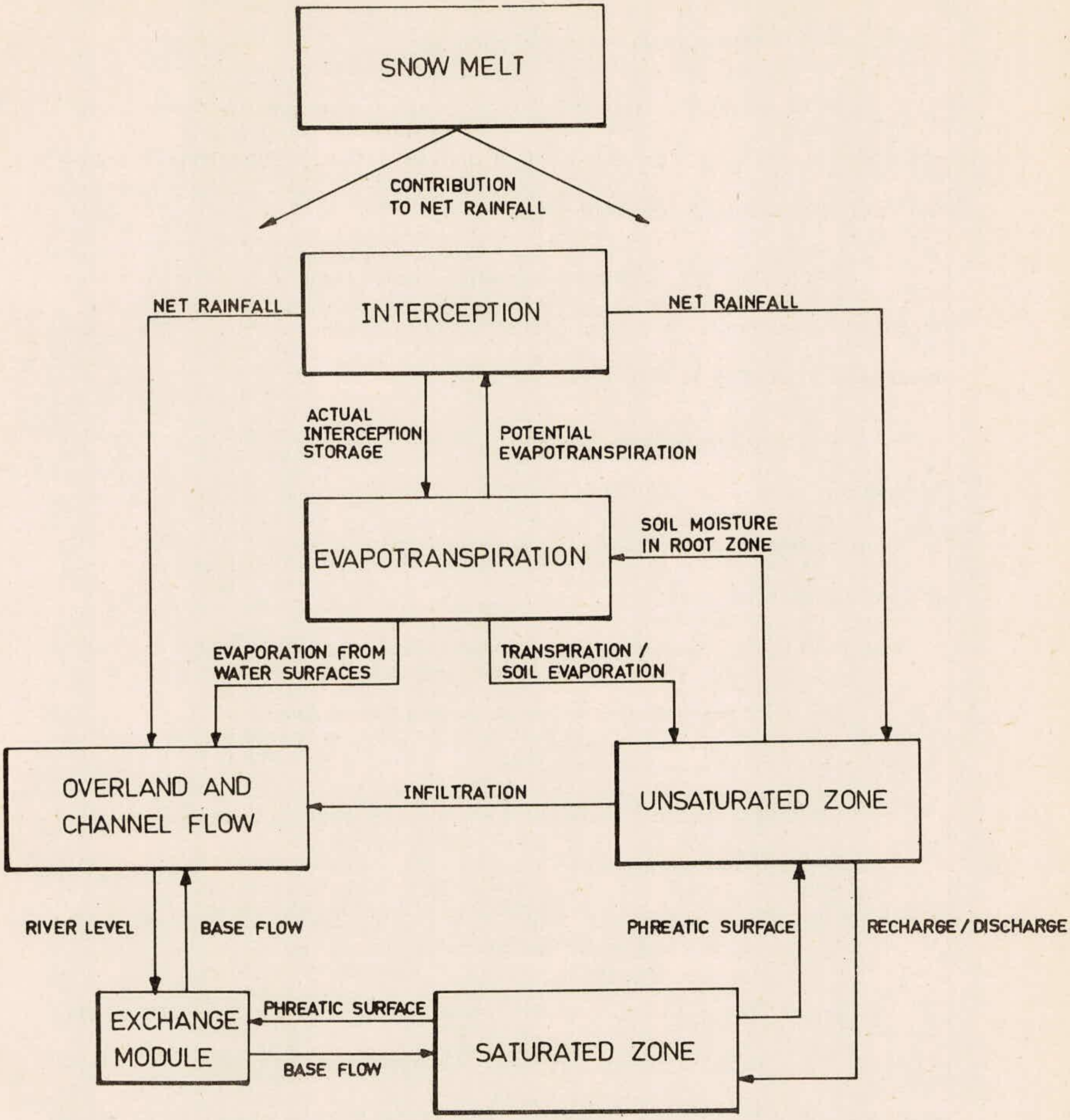


Figure 5 : Data flow between components of SHE

2.3 Different Models

2.3.1 SHE (System Hydrologique Europien)

A large scale attempt to develop a physically based model, was made jointly by Institute of Hydrology (U.K.), SOGREAH (France) and Danish Hydraulic Institute (DHI).

The computer programme 'SHE' comprises of five process oriented components and one 'FRAME' for organisation. The five processes included in SHE are :

1. Interception/Evapotranspiration
2. Overland and channel flow
3. Unsaturated flow
4. Saturated flow
5. Snow melting

The information input includes the following:

(a) topographic information,

(b) rainfall and climatologic station description

(c) vegetation types,

(d) soil types and depths including level of the impermeable bed and a series of parameters.

The detailed description can be seen in DHI (1986). The flow chart, taken from above reference, showing the transfer of valid internal boundary data between the component, is given Fig.5.

The interception process is represented by Rutter model (Rutter et al 1975). It is stated that canopy storage and drainage parameters can be estimated by experiments. (Rutter et al, 1975). The model accounts the amount of water stored on the canopy.

The following equation is solved analytically.

$$\frac{dc}{dt} = Q - K\ e^{b(c-s)} \qquad \ldots (8)$$

where,

$Q = P_1\ P_2\ (P - E_p\ C/s)$ when $c < s$

$Q = P_1\ P_2\ (P - E_p)$ when $c \geq s$

C is the actual depth of water on the canopy

S is the canopy storage capacity (may be interepted as the minimum depth of water required to wet all canopy surfaces)

P is rainfall rate

P_1 is the proportion of ground in plan view hidden by vegetation

P_2 is dthe ratio of total leaf are to area of ground cover by vegetation.
P_2 is restricted to ≤ 1

E_p is potential evapotranspiration

k and b are drainage parameters.

t is time.

The model parameters are estimated from rainfall, net rainfall below the canopy and evapotranspiration. The interception component is limited to include only one vegetation type within each grid square.

For the prediction of actual evapotranspiration rates, Penman-Monteith equation (Monteith, 1965) is used.

The following hydrodynamic equations have been solved by explicitly finite difference scheme.

$$\frac{\partial h}{\partial t} + \frac{\partial (vh)}{\partial x} + \frac{\partial (vh)}{\partial y} = q \qquad \ldots (9)$$

$$\frac{\partial h}{\partial x} = So_x - S_{fx} \qquad \ldots (10)$$

$$\frac{\partial h}{\partial y} = Soy = S_{fy} \qquad \ldots (11)$$

where,

h is water depth, a function of x,y

t is time coordinate

x, y are horizonal space coordinates

u, v are flow velocities in x and y directions respectively (both are functions of x, y)

q is net precipitation minus infiltration (function of x, y, t)

S_{ox} is bed slope in x direction

S_{oy} is bed slope in y direction

S_{fx} is energy slope in x direction

S_{fy} is energy slope in y direction

All the slopes are functions of x and y.

Strickler/Mannings equation is used to find energy slope. It may be noted that inertial terms are neglected in the momentum equation.

One dimensional equations are solved by implicit finite difference scheme for the channel flow.

Further details can be found in DHI (1986), Beven and O'Connell (1982), and in abbot et al (1978).

2.3.2 C S U Model

This is a non-linear, deterministic and distributed model. It accepts the input: (i) dthe hyetograph of precipitation as measured on or near the watershed, (ii) the geometry and topography as determined from a map of the area, (iii) two parameters, which relate to the surface roughness characteristics and the regime of flow (laminar or turbulent) which would be expected to occur, and (iv) the infiltration characteristics for previous areas. The watershed is assumed to be a series of planes cascading on to other planes are connected one another by channels are shown in Fig. 6

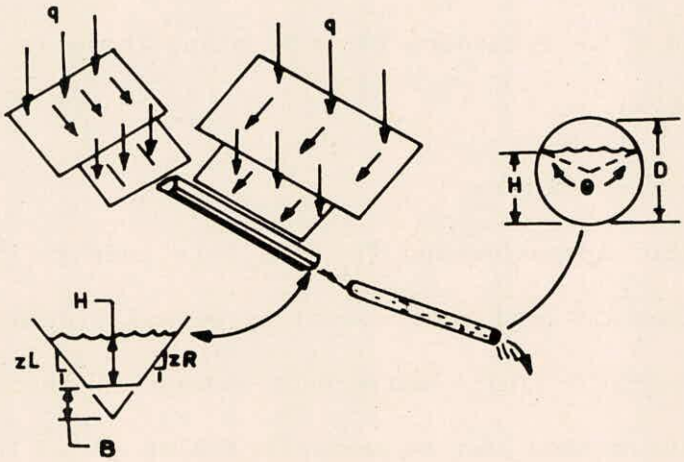


Figure 6 : Watershed represented as a kinematic Cascade (CSU)

The planes are either impervious, i.e. streets or parking lots or are pervious, i.e. rural open areas or lawn areas. The channels are assumed to have either a traphezoidal or circular corss section.

A non-dimensional infiltration equation is used in this model as given below:

$$f_x = 1 + (1-\alpha)\ (t_* - t_{o*})^{-\alpha} \qquad \ldots (12)$$

where, $f_* = \frac{f}{f_\alpha}$

α is a parameter unique to a soil, initial moisture and rainfall rate

$t_* = \frac{t}{T_o}$

f is the infiltration rate

f_α is the final infiltration rate

t is time

T_o is normalizing time

The use of this equation requires the determination of four parameters f_∞ , α , To and t_o*. Procedure for evaluating these are given in Rovey et al (1977).

Surface and Channel Routing

Kinematic approximation ($S_o = S_f$) is made to the gradually varied flow equations and then solved by method of characteristics. In this Lax-Wendroff finite difference scheme is used. Complete details of this method can be seen in Kibler et al (1970). Two types of friction formula were used (Chezy and Darcy-Weisbach), in CSU model.

The difference between routing runoff over planes and through channels is that upstream inflow into a plane is given in discharge per unit width of the plane, while upstream inflow to a channel is the total discharge from the pervious segment. For watershed area computation, the width of the channel is assumed to be negligible width. Therefore, rainfall directly falling onto the channel is not considered in routing. The lateral inflow to a channel is the discharge per foot of width received from an adjacent plane.

Two geometrical shapes were considered by CSU. They are circular and trapezoidal cross sections.

A four point implicit finite difference scheme is used to solve the kinematic flow equations.

2.3.3 USDA model (Ross 1978)

Ross et al (1976) developed a procedure to use soil mapping units and land use data to sub-divide the watershed into homogeneous response unit, where rainfall excess was determined from a soil moisture model. A parameteric approximation was used in lieu of more detailed numerical solution of the partial differential equations of unsaturated flow. The primary component of the soil moisture model was the simulation of infiltration.

Routing of rainfall excess is done by solving one dimensional, unsteady partial differential equations of continuity and momentum with kinematic wave approximation using FEM. In watershed modelling applying FEM is analogous to sub-dividing the drainge area into homogeneous response units and determining the hydrologic response of each. The different model components in their model are as follows precipitation excess:

The Holton equation in the following form is used:

$$f = as^{n} + f_{c} \qquad \ldots(12)$$

where,

f- is infiltration is (in./hr.)

a- is coefficient to index the effect of cover condition

S- is unfilled storage space to a restrictive layer in(in.) usually assumed to be the A Horizon

f_c-final infiltration rate in (in/hr)

n a coefficient that is assumed to be a function of soil type and is defined as the ratio of potential plant available water to the potential gravitational water in the A Horizon

Ross et al used the soil mapping units, land use to isolate homogeneous land units. This homogenity only implies a reduction in the heterogenity of the original system. The hydraulic characteristics of these homogeneous units can be considered constant. This is an assumption subjected to considerable debate. These units are called HRU. The procedure outlined by Li et al (1977) has been used to define HRU. However, objective criteria for defining HRU for a given problem do not exist.

Surface and Channel routing :-

A watershed will consist of numerious sub-sheds unless a field or unit source drainge system is being studied. All flows that drain the finite sized elements are assumed to be concentrated along a line element. Element boundaries may be irregular to fit the natural drainage to each line element. Element areas are employed solely for obtaining lateral flow into the element. HRU's often were very small, the flow distance was in some cases very short (2 to 5 feet). To obtain numerical stability very small time steps are required, if finite elements used are equal to HRU. Hence in one finite line element there were number of HRU's. The properties of the element are weighted average of the HRU's according to their area.

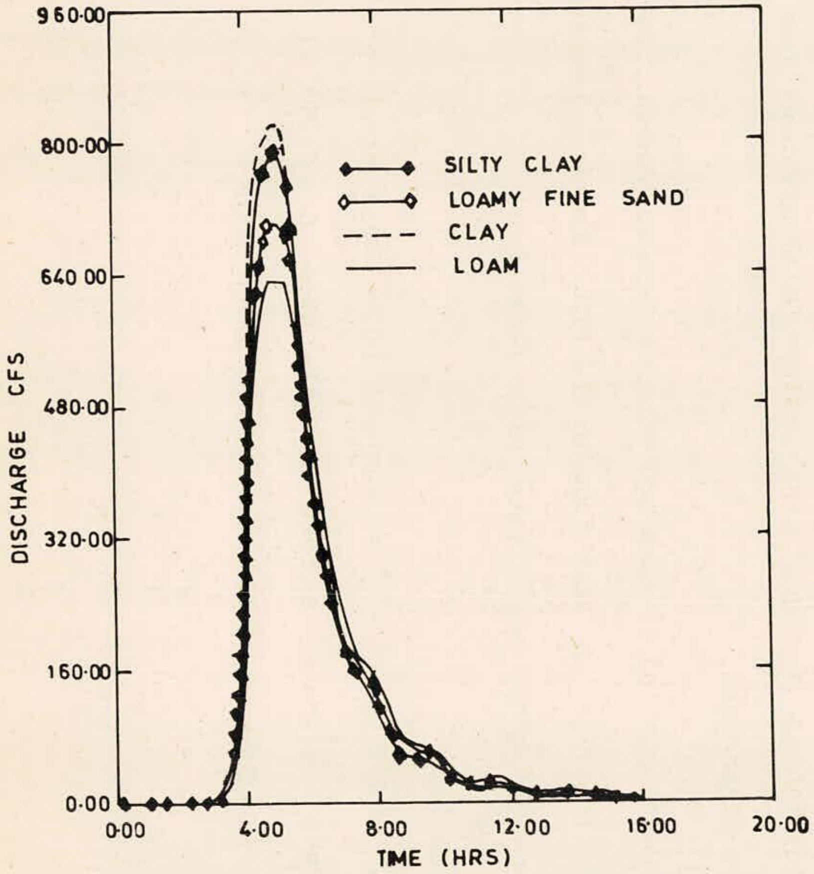


Figure 7 : Effect of soil texture on the discharge hydrograph

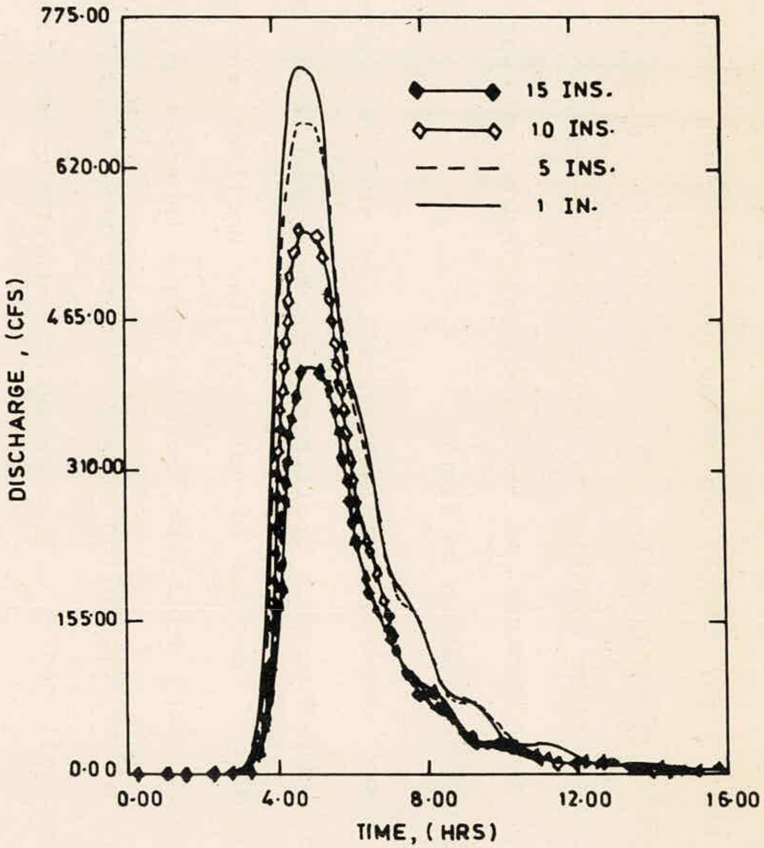


Figure 8 : Effect of soil depth on the hydrology

The soil type, slope class and erosion class combine to identify a soil mapping unit. The soil textural classification and depth of 'A' horizon combined to define the soil storage capacity. The effect of soil texture on the discharge hydrograph was given by Ross et al (1976) as shown in Fig.7.

Simulation of excess rainfall will be very sensitive to changes in soil depth because infiltration is described by the Holton equation as a direct function of volume of the unfilled pore space. The effect of the soil depth are shown in Fig.8 (Ross et al, 1976). The parameter 'a' in the Holton equation in the soil moisture model depends on the soil cover. This parameter differs greatly between impervious and other cover conditions. However it does not differ very much between different cover conditions. It is well recognised that the moisture condition existing in the drainage area prior to a storm event is a significant factor in determining how much water will be discharged.

The Manning's 'n' is used to index surface roughness. Roughness is assumed to be invarient with flow in the FEM. Research has demonstreated that 'n' often will vary with flow depth.

Numerical Stability

When explicit scheme is used to solve Ross et al stated that the stable solution is resulted only when $\Delta t < 20\%$ of the time step as per Courant condition which is given below:

$$\Delta t \leq \frac{\Delta x}{V+c} \qquad \ldots (13)$$

where,

Δt is allowable time step in Sec.

Δx is the flow distance m

v is flow velocity m/sce.

c is wave speed m/sec.

It has been found that Δt for hydraulic routing of overland flow on pervious type surface can be of the order of 5 to 6 times Δt for the channel.

2.3.4 MULTSED OF LI, SIMON and others

The Multiple Watershed Sediment Model (MULTSED) was developed to simulate the rainfall-runoff relationship and the associated sediment yield from large watershed. Since large watersheds are non-homogeneous in soils and vegetation and have a complex topography, it is necessary to divide a large watershed into smaller units that are considered homogeneous and gemetrically simple. Using a system of planes, sub-watersheds and channels, MULTSED can simulate the storm runoff and sediment yield from an entire basin.

There are four types of response units used, viz. 1) a single plane SEDWAT unit, 2) an open book SEDWAT unit, 3) a channel which is a large channel interconnecting the other units, and 4) a connection.

Infiltration with respect to time is computed using an explicit model based on Green and Ampt infiltration equations. as given in Li, et al (1976).

An analytical solution to the continuity, the kinematic wave approximation to the momentum and cross-section geometry equations is used to route water in the plane and sub-watershed units.

The partial differential equations of fluid flow are solved by the method of characteristics. An infiltration routine is combined with the numerical channel routing procedure to account seepage losses. The procedure is identical to that of overland infiltration routine, except for the addition of the pressure head due to the depth of water.

This model was tested applying on to a small agricultural watershed near Watkinsville, Georgia and to Walnut Gulch, Arizona watershed which is of 57-7 square miles. Li et al (1979) concluded that satisfactory agreement between simulated and recorded hydrographs were obtained.

2.3.5 NWSRFS Model

A computer programme developed by National Weather Service River Forecast System takes continuous record of six hour basin mean precipitation and gives routed flow as the output. The infiltration analysis is similar to Stanford model. Evaporation from stream surface and evapotranspiration from ground water are computed jointly in NWSRFS. The lag and K channel routing is used.

2.3.6 ILLUDAS

The Illinois Urban Drainage Area Simulator uses actual hyetograph uniformly distributed over the basin and physical basin parameters to predict storm runoff from both directly connected impervious area and contributing grassed area.

The drainaged basin are divided into sub-basins. In each sub-basin storm runoff hydrographs are computed from directly connected impervious area and contributing grassed area. A simple storage routing technique is used to route the inflow hydrograph.

Rainfall excess is computed after satisfying the infiltration and depression storage 0.2 inches. Antecedent moisture content (AMC) and hydrologic soil type are specified as input data. The Horton's infiltration equation is used to simulate the infiltration process in pervious areas. The widely used Horton's infiltration equation is :

$$f = f_c + (f_o - f_c)\, e^{-kt} \qquad \ldots (14)$$

where,

f is infiltration rate at time t (in/hr)

f_c is final infiltration rate (in/hr)

f_o is initial infiltration rate (in/hr)

k is a shape factor

t is time since start of rainfall hr.

A simple storage routing is used to obtain routed hydrograph from runoff hydrograph obtained using time area curve.

2.3.7 UROM - 9 (MINNESOTA)

A deterministic runoff model capable of continuous real time operation was developed by Bowers et al (1968).

The average precipitation recorded at the gauges of Minneapolis-St.Paul district were computed using Thiessen weights,. The rainfall excess from impervious area is computed by deducting 'loss' from rainfall as below.

$$\text{Loss} = \text{Rainfall} \times C\, e^{-K\,(\text{accumulated loss})}$$

where,

C and K are constant for a watershed and they are assumed to be 1.00 and 2.0 respectively. For impervious areas, initial values of the accumulated loss were assumed to zero and infiltration process is neglected. The rainfall excess from pervious areas is computed using a modified Holton's infiltration equation by Huggins and Monk (1970).

$$f = f_c + \left[\frac{(T - \text{accumulated loss})^K}{T}\right] \qquad \ldots(15)$$

where,

f -is potential infiltration rate (L/T)

f_c -is constant equilibrium rate assumed to be 0.2 in/hr.

T -the total available soil moisture storage in the soil above the restrictive layer assumed to be 2.0 inches

K -is a constant taken as 0.7

A -is the increase in infiltration rate under dry condition assumed to be 2.0 in/hr.

Initial accumulated loss for pervious area is assumed to be 0.25 inches.

Runoff hydrographs at 15 main inlets are computed using a triangular synthetic hydrograph approach. The characteristics of this synthetic hydrographs T_p, Q_p and T_b are computed using the SCS curve number method.

The progressive average lag method is used to perform the routing with constants having been determined from comparison with similar routing using the method of characteristics.

Battelle (1973), further developed this model to include quality simulation and dynamic programming. He has used kinematic wave equation routing.

2.3.8 EPA Storm Water Management Model (SWMM)

This is a non-continous detailed computer based mathematical model that can determine the amount of runoff and pollutants from a storm, route the runoff through a combined or seperate sewer system and treatment facilities. The model determines the pollutographs.

For the computation of hydrographs, the drainge basin may be conceptually represented by a net of hydraulic elements, i.e., subcatchment, gutters and pipes. Subcatchments are idealized rectangular areas with uniform slope ground cover and soil types. Each subcatchment can have three kinds of area to contribute to runoff: 1) impervious area with zero detention (immediate runoff), 2) impervious area with detention, and 3) previous area.

The model neglects intereption and evapotranspiation processes since the storm duration is short. The Horton's infilration capacity curve with no time off set is used. The equation of continuity and Manning's equations are used to simulates overland flow. Uniform depth of flow is assumed in the overland flow plane along its length. Also, a steady flow is assumed to occur within each interval of time.

Three options for routing are available; viz. 1) runoff block where Manning's equation is used and is recommended when sewer pipes are less than 2-3 ft. in diameter, 2) transport block where finite difference method is used to solve the simplified version of the momentum and continuity equation:

$$Q = \frac{1.49}{n} AR^{2/3}(S_o - \frac{\partial y}{\partial x} - \frac{v}{g} \frac{\partial v}{\partial x})^{1/2} \qquad \ldots (16)$$

where,

Q- is discharge (L^3/T)

A- is area of cross section of flow (L^2)

R- is hydraulic depth (L)

S_o-is bed slope

Y- is depth of flow (L)

V- is velocity (L/T)

X- is space coordinate

EPA SWMM is very complex and require large core memorie and computer time. More details can be had in Huber (1975).

2.3.9 UCUR Model

The University of Cincinnati Runoff Model, five sub-models, which simulate individually the hydrologic process involved in runoff. These are: 1) infiltration, 2) surface retention, 3) overland flow, 4) Gutter flow, and 5) sewer routing.

Initially the total drainage is divided into a number of small sub-catchments. Each type of sub-catchment has uniform slope and is identified with respect to ground cover and overland flow length. The input data include: 1) rainfall hyetograph,

2) Horton's infiltration parameters, 3) depression storage for pervious and impervious area, 4) gutter data and pipe data.

Supply to depression storage starts when the infiltration goes to the final infiltration rate Linsley's (1949). equation as given below was used:

$$S = (i - f)\ e^{-(p - F)/S_d} \qquad \ldots (16)$$

where,

S- is depression storage supply in (in.hr.)

i- is rainfall intensity in (in./hr)

f- is actual infiltration rate in (in./hr)

p- is accumulated volume of water precipitated in (in.)

F- is accumulated volume of water infiltrated in (in.)

S_d-is total depression storage capacity of the basin (in.)

The depression storage capacity is an input. After calculating values of infiltration and depression storage supply from the rainfall intensity at any time, the rainfall excess which produces the overland flow is obtained for each sub-catchment.

The overland flow is computed using the Manning's equation. An empirical relationship found between outflow depth and detention storage for reproducing experimental hydrographs (by Linsley) is used.

$$y = D \quad [1.0 + 0.6\ (D/De)] \qquad \ldots(17)$$

where,

y- is outflow depth in inches

De-is detension storage required at equilibrium in/unit area

D- current detension storage in/unit area

A storage routing procedure is used.

$$r - q = 60 \frac{dD}{dt} \qquad \ldots(18)$$

where,

$r = i - f - s$

S is depression storage

Newton Raphson iterative scheme is used to solve the combined equation for overland flow obtained from equations (16), (17) and (18).

Further details can be seen in Preul et al (1970).

2.3.10 Stanford Model

This is one of the earliest efforts to provide digital simulation of hydrologic process. Both SSARR and stanford models were developed in late 1950's. The Stanford model was initially writeen in ALGOL language and rewritten in FORTRAN at University of Kentucky, Ohio State University and at other places also.

Precipitation and potential evapotranspiration are the major inputs. An assumed or a given moisture condition is taken. The Chezy-Manning's equation is used to derive relation between surface detention, parameters concern with overland flow and runoff from overland flow.

2.3.11 SSARR - TINGSANCALL composite model

Overland flow:

In this model the total runoff is computed as the product of rainfall and runoff coefficient which is the function of computed soil moisture. The total runoff is then decomposed into surface sub-surface and baseflows which are routed and added up again as the local inflow to the river. In routing surface, sub-surface and baseflows, the following storage equation is used:

$$I - O = ds/dt \qquad \ldots(19)$$

In this equation, I and O are inflow and outflow, S is the storage and t is the time. The SSARR watershed model routes the flow through a series of successive increments of lake type storage in which the relationship between s and outflow o is given by:

$$\frac{ds}{dt} = T_s \frac{do}{dt} \qquad \ldots(20)$$

where,

T_s is the time of storage and is not necessarily a constant.

Combining the above two equations, i.e. equations (17) and (18):

$$\frac{do}{dt} = \frac{I - O}{T_s} \qquad \ldots(21)$$

Channel model:

Both kinematic and dynamic flood routing techniques are considered in channel routing. The SSARR channel model exploits kinematic routing technique is used to route the flow. The energy slope S_f is assumed to be well represented by the bed slope, S_o of the river. The governing equations for the SSARR channel model are the storage equation (21) given aboveand the simplified momentum equation:

$$T_s = \frac{KTS}{Q^n} \qquad \ldots(22)$$

KTS and n are impirical constants and Q is the discharge.

TINGSANCALI (1979), has used dynamic routing models like Node and Branch model and single channel model given by Stapel et al (1970) and Frye (1966) respectively.

In dynamic routing technique which is more complicated than the kinematic routing technique, the energy slope S_f is basically expressed as:

$$S_f = S_o - \frac{\partial y}{\partial x} - \frac{v}{g} \frac{\partial v}{\partial x} - \frac{1}{g} \frac{\partial v}{\partial t} \qquad \ldots(23)$$

where,

y- is the depth

v- is the velocity

g- is the gravitational acceleration

x, t- are space and time accordinates.

The cosntinuity equation for the Node and Branch model is the storage equation (19). But for single channel model, the continuity equation is given as:

$$\frac{\partial Q}{\partial X} + B \frac{\partial H}{\partial t} = 0 \qquad \ldots(24)$$

where,

B- is water surface width,

H- is the water level.

Flood plain model:

In addition to SSARR flood plain model Tingsanchali (1974) storage flood plain model was also used. The spillage and return flow are computed using the weir equations under submerged or non-submerged conditions.

Reservoir Model:

The SSARR reservoir model is used to route the flow through the reservoir using the storage equation.

Application:

This model was applied to Chao Phraya river basin. The SSARR watershed channel flood plain and reservoir models were used in the upper Chao Phraya river basin. In the lower Chao Phrya river basin to Gulf of Thailand the flow was influenced by tidal currents and backwater effects and the Node and Branch model and single channel model are therefore sdused. Although Node and Branch model can route in the down-stream portion of Chao Phraya river as a single channel model, the latter was prefered because of - simplicity.

2.3.12 Sacramento Model

Burnash and others developed a conceptual streamflow simulation system. The model is based on a system of percolation, soil moisture storage drainage, and evapotranspitation characteristics to represent the hydrological processess. The permeable portion of the basin is divided into upper and lower zones

These zones are further divided into tension water storage and free water storage. Tension water is considered as that water closely bound to soil particles and is available for evapotranspiration. Tension water storage should be filled up before moisture become available to enter free water. Free water can descend to lower zone by percolation or can move laterally to produce interflow. Percolation is controlled by the contents of the upper zone free water and deficiency of lower zone moisture volume. When precipitation rate exceeds the percolation rate and the maximum interflow drainage capacity. The upper zone free water capacity is filled completely and the excess rainfall will result in surface runoff. The free water storage of both the zones fill simultaneously from percolated water and drain independently at different rate giving variable ground water recession. Unit hydrograph method is used to compute runoff. Baseflow from lower zone is added to the channel inflow. Four layer Muskingum channel routing hydrograph is adopted.

The other details can be seen in Burnash (1973)

2.3.13 Purdue Model

Huggins, L.F. et al (1970) developed a computer programme in FORTRAN IV. This programme takes rainfall hyetograph, antecedent watershed condition, infiltration coefficients and topography of the watershed and calculated surface runoff. There are four components in this model, viz. 1) interception, 2) surface detention, 3) infiltration, and 4) overland flow.

The surface storage-depth relationship is expressed as below:

$$y = A\,x^{B} \qquad \ldots (25)$$

where,

y- is surface

x- is detention depth

A- and B are coefficients which were determined by a least square method on the observed data.

A modified version of Holtan's equation is used in infiltration process (as given in equation (12)).

Surface runoff is generated using kinematic model using Manning's equation. The model has been tested on small watershed.

2.3.14 SCS TR 20 and TR 55

This programme computes surface runoff due to a given drainfall distribution, develops runoff hydrographs and routes them.

The SCS runoff computation technique was derived from studies of experimental plots which had various soil and vegetative conditions. It was originally developed to compute the excess from a 24 hour rainfall on a small watershed. The equation is:

$$Q = (P - 0.25)^2/(P + 0.85) \qquad \ldots(26)$$

where,

Q- is direct runoff in (in)

P- is rainfall in (in)

S- is potential maximum retention andis related to curve numbers developed by them.

Three antecedent conditions (dry, normal or wet) are used. Using the curve numbers rainfall excess was computed and then by unit hydrograph techniques runoff hydrographs are obtained. Reservoir routing is carried out on this and the channel routing is done using convex routing method. Details can be seen in SCS Technical Release 20 (1965). The TR 55 of SCS is a guide for field personnel in estimating the effect of land use changes and structural measure.

2.3.15 USDAHL - 70

Holtan et al (1971) developed this programme to serve the purpose of agricultural watershed engineering by providing information on the moisture regime, over land flow, evaporation on each soil zone. This programme is expected to be of use for design of level terraces in contour strip cropping etc. It also provides water yields on a continuing basis and calculates flood hydrographs.

The input includes: (a) continuous record of average weighted rainfall for the watershed, (b) information on hydrological grouping of soils and land use, (c) soil profile description, (d) weighted average of hydrologic capacities (porosity, field capacity, wilting point and antecedent soil moisture), (e) recession flow characteristics to route channel flow and sub-surface flow.

A watershed is assumed to have certain hydrologic response zones for computing infiltration, evapotranspiration and overland flow, zones (typify the elevation sequence of uplands, hillsides, and bottom lands) are always numbered in a downslope order because computations assume that some of the runoff will cascade over successive zones.

Rainfall excess is computed after subtracting depression storage, evaporation and infiltration.

Soil moisture accounting method is used for accounting evaporation, infiltration.

Daily evapotranspiration potentials are calculated considering published pan evaporation data, gorwth index of crop and soil moisture condition.

Infiltration is based on the Holton equation:

$$f = (GI)\ (a)\ (S_a)^{1.4} + F_c \qquad \ldots(27)$$

where,

f- is infiltration capacity in (in/hr)

GI-is growth index in percentage of maturity,

a- is infiltration capacity in inches per hour per $(\text{inch})^{1.4}$ of available storage (index of surface connected porosity).

S_a-is available storage in the surface layer (inches) in the 'A' horizon of the agricultural soil, and

f_c-constant rate of infiltration after prolonged wetting in (in/hr).

Rainfall in excess of infiltration is routed across each soil zone and cascaded, subjected to further infiltration across designated subsequent zones enroute tothe channel. Overland flow is computed using continuity equation and the following type of momentum equation:

$$q_o = a\ D^n \qquad \ldots(28)$$

where,

q_o-is overland flow in (in/hr),

a -is a coefficient dependent on the roughness, length, slope

n -is 3 for laminar flow, and 1.67 for turbulent flow.

Channel flow and sub-surface return flows are routed by simultaneous solutions of continuity equation and a storage function.

3.0 PROBLEM DEFINITION

The objective here is to compute runoff hydrograph due to the quick response of a watershed to an incident precipitation at a given site on a stream. The following data are basically needed for this purpose:

1. Precipitation data at raingauge stations within the catchment;
2. Length, width and slope of the plane surfaces comprising the catchment;
3. Length, width, slope of channels draining these plane surfaces;
4. Coefficient of friction (Manning's 'n') for each of the identified units (Planes and channel reaches)

Since precipitation recorded at the gauging stations from the basic data, the methodology for the above should invariably begin reducing them to precipitation excess. The details of the watershed consider as an example of application of the methodology given in section 4.0, are given below.

3.1 Description of the Watershed

Watershed as shown in Fig. 9 is choosen from Ross et al (1978) for the development of a model. This watershed is assumed to comprise of eight units such that the soil and other important characteristics in each unit can be assumed to be homogeneous. The land use characteristics of soil properties are given in Table 1.

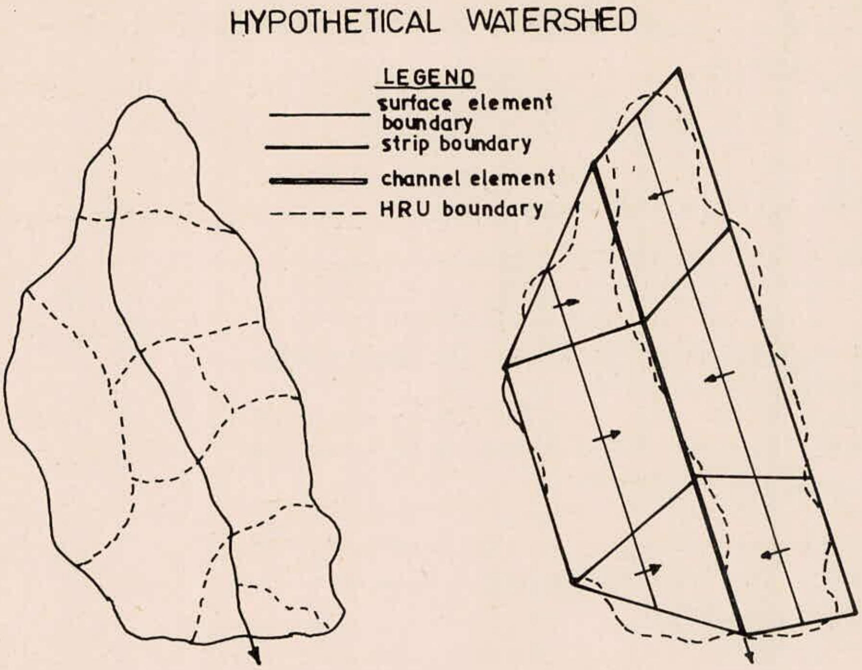


Figure 9 : Watershed studied

Figure 10 : Approximating the study area

TABLE 1 : LAND USE OF SOIL PROPERTIES OF THE UNITS

Unit No.	Soil Texture	Depth of A Horizon(cm)	Land use	Soil hydrology group
1.	Silty clay loam	20.32	woods	B
2.	Silty clay loam	25.4	woods	B
3.	Silt loam	15.24	woods	B
4.	loam	25.4	Pasture	B
5.	loam	12.5	Row crop	B
6.	loam	20.32	Row crop	B
7.	Sandy loam	7.62	Residential	B
8.	-	-	Impervious	-

A regular geometry is superimposed as shown in fig.10. The geometry and hydraulic characters of the planes and channel are given in Table 2 and 3.

Table 2: CHARACTERISTICS OF PLANE SURFACE

Element	Length (ft)	Average width (ft)	Slope (ft/ft)	Manning's coefficient
A1	1000.0	550.0	0.016	0.388
A2	1000.0	1650.0	0.010	0.388
B1	750.0	2200.0	0.016	0.386
B2	750.0	2200.0	0.010	0.370
C1	1000.0	2875.0	0.012	0.390
C2	1000.0	2425.0	0.008	0.353
D1	750.0	3250.0	0.012	0.355
D2	750.0	2550.0	0.008	0.343
E1	1000.0	550.0	0.008	0.300
E2	1000.0	1650.0	0.005	0.280
F1	750.0	1975.0	0.008	0.237
F2	750.0	2125.0	0.005	0.208

TABLE 3 : CHARACTERISTICS OF CHANNEL

Element	length (ft)	Slope (ft/ft)	Manning's 'n'	Width		Depth of Channel (ft)
				Channel (ft)	Flood plain (ft)	
1	2200	.008	.10	10.0	100.0	5.0
2	2200	.005	.09	20.0	150.0	5.0
3	2200	.003	.08	30.0	200.0	5.0

Since a given computational element comprise of oneor more homogenous units, areal weighting factors as given in Table 4 is used.

TABLE 4 : AREAL WEIGHTING FACTOR OF ELEMENTS

Element	Homogeneous units							
	1	2	3	4	5	6	7	8
A1		.75			.25			
A2	.70	.15			0.15			
B1	.70				0.30			
B2	.40				0.60			
C1		.90		.10				
C2		.20		.15	0.15	0.50		
D1			.40	.30	0.30			
D2			.10	.25	0.25	0.40		
E1				1.0				
E2				0.60			.40	
F1				0.20			.70	.10
F2				0.30			.45	.25

The six hour storm event applied in this watershed is as shown in figure 11. The watershed's response to this storm in terms of runoff hydrograph at the outlet 'T' is proposed to be computed.

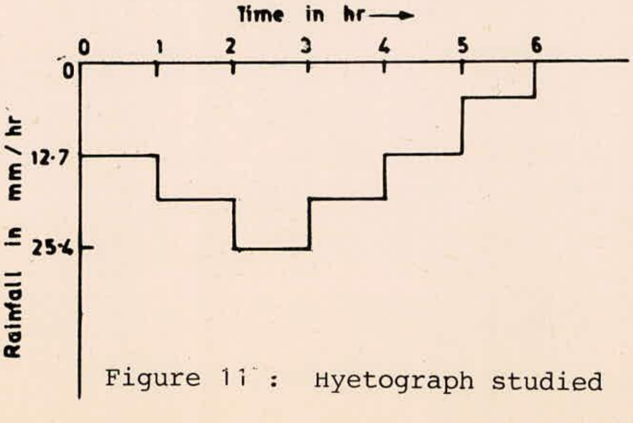


Figure 11 : Hyetograph studied

4.0 METHODOLOGY

The problem explained above was solved in two stage. At the first the rainfall excess was computed and routed over the plane surfaces using SOIL. FOR. This produces the required lateral flow to the channel. After the computation of this flow through out the channel length routing in the channel is done by a sub-programme CHANNEL. FOR. The procedure used in the above are briefly given below.

4.1 SOIL. FOR

In this the rainfall hyetograph is accepted as an input. The computations proceeds in DT time steps. For every DT the infiltration is computed using the following Holtan's equation as given in equation (12):

$$f = a\, s^n + f_c$$

This type of the equation is choosen mainly because it is based on storage concept which can easily be determined and the coefficient can be obtained easily. The rainfall in excess of this infiltration is computed for all time steps. This excess is routed over the planes as follows.

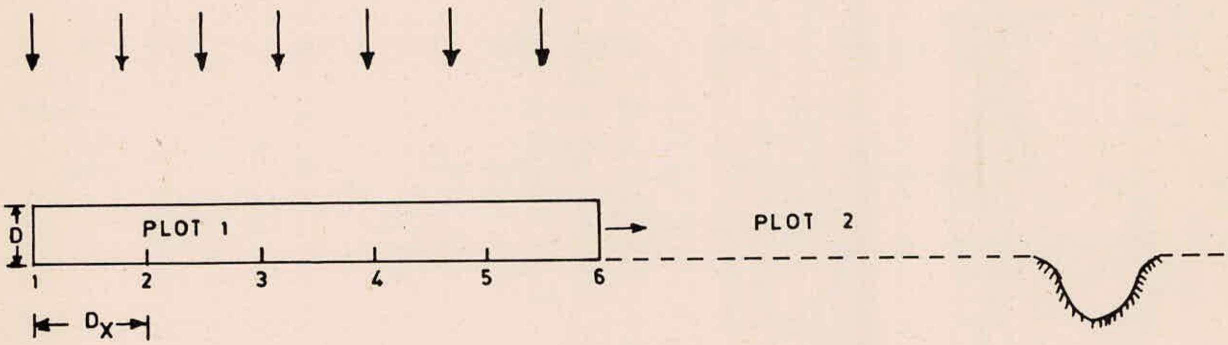


Figure 12 : Sketch of Surface flow with grid points on Plot 1

At section 1 it is assumed that there is no accumulation of rain water. In order words, the depth of rainfall is imposed as the boundary condition at section 1 of the first plot adjacent to the catchment boundary. This is reasonably correct since this section would normally be on a ridge. It is also assumed the flow is essentially unidirectional leading to the channel. The following equations are used to route the flow considering unitwidth:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad \ldots (28)$$

$$S_o = S_f \qquad \ldots (29)$$

where,

A is the area of cross section of flow (L^2)

Q is the discharge (L^3/T)

q_L is the rainfall excess per unit length

S_o is the bed slope

S_f is the energy slope

The use of last equation (29) implies that frictional resistance to flow is over come by the gravitational pull. This is known as kinematic approximation.

In finite different form:

$$\frac{D^i_{t+Dt} - D^i_t}{DT} + \frac{Q^i_t - Q^i_t}{DX} = \text{Rainfall excess} \qquad \ldots (30)$$

$$Q_i = \frac{1}{n} D^i_t \, (D^i_t)^{2/3} \quad S_o^{1/2} \qquad \ldots (31)$$

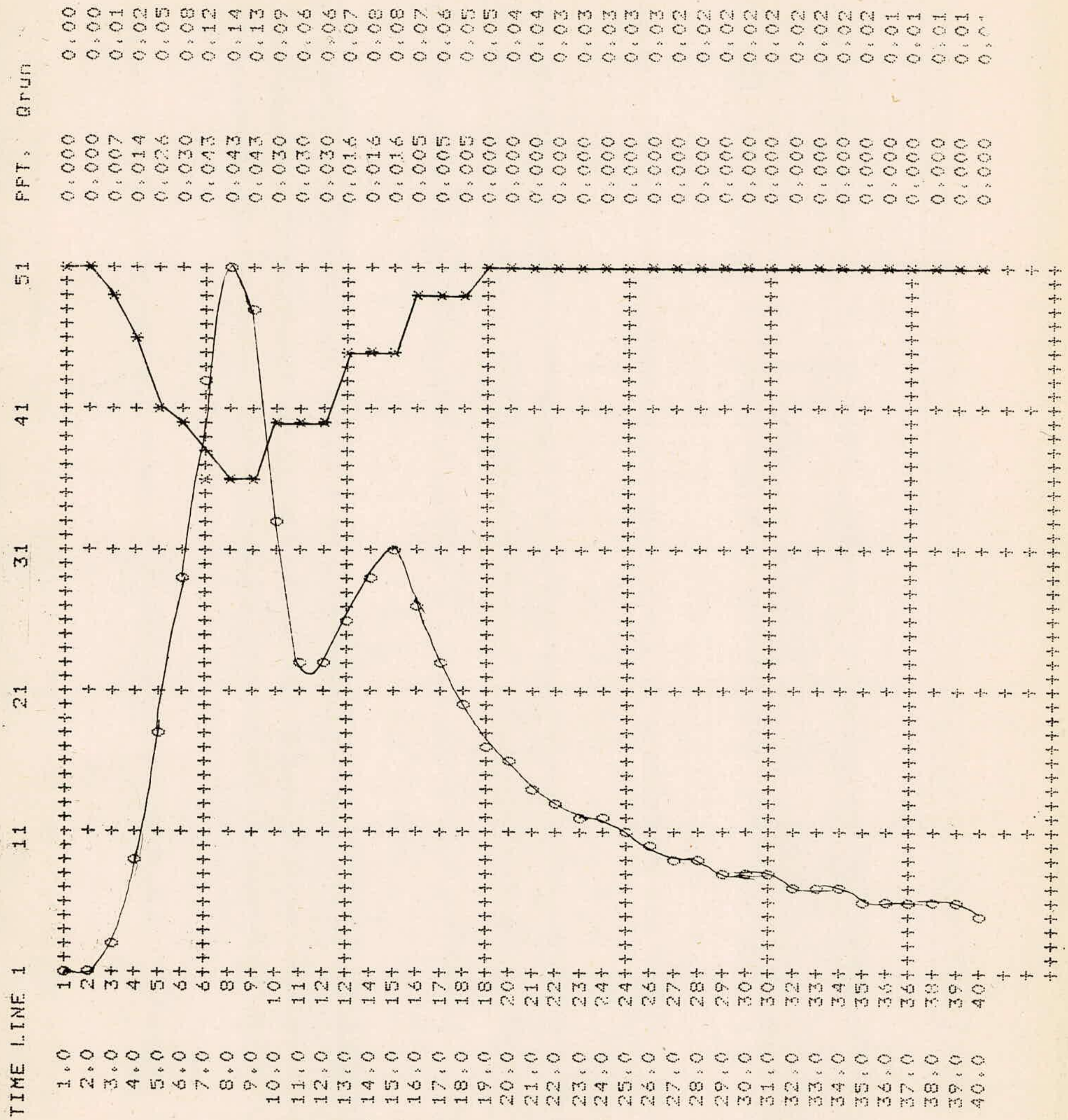
The discharge at various sections are computed using the above Manning's equation using the depth of flow at these sections. Initially these depths equal to rainfall excess. When the flow from or to the adjacent section, the depth is adjusted appropriately as per continuity equation. Successively the flow is routed through the sections. The routed flow at the end of the first plot is width adjusted to form the boundary condition for the second plot as follows:

$$Y'(t) = \text{Rainfall excess} + \text{Routed flow} \times \left(\frac{\text{width of 1st plot}}{\text{width of 2nd plot}} \right) \qquad \ldots (32)$$

The computer programme is given in Appendix III. A sample input and the output are given in Appendix IV.

4.2 CHANNEL.FOR

In this continuity and momentum equations are solved by method of characteristics as explained in the Appendix I. The computer programme and the results are given in the Appendix V and VI respectively. The input to this programme comes from SOIL.FOR



```
TIME   FPT,   Qrun
 1.0  0.000  0.00
 2.0  0.000  0.00
 3.0  0.007  0.01
 4.0  0.014  0.02
 5.0  0.026  0.05
 6.0  0.030  0.08
 7.0  0.043  0.12
 8.0  0.043  0.14
 9.0  0.043  0.13
10.0  0.030  0.09
11.0  0.030  0.06
12.0  0.030  0.06
13.0  0.016  0.07
14.0  0.016  0.08
15.0  0.016  0.08
16.0  0.005  0.07
17.0  0.005  0.06
18.0  0.005  0.05
19.0  0.000  0.05
20.0  0.000  0.04
21.0  0.000  0.04
22.0  0.000  0.03
23.0  0.000  0.03
24.0  0.000  0.03
25.0  0.000  0.03
26.0  0.000  0.03
27.0  0.000  0.02
28.0  0.000  0.02
29.0  0.000  0.02
30.0  0.000  0.02
31.0  0.000  0.02
32.0  0.000  0.02
33.0  0.000  0.02
34.0  0.000  0.02
35.0  0.000  0.02
36.0  0.000  0.01
37.0  0.000  0.01
38.0  0.000  0.01
39.0  0.000  0.01
40.0  0.000  0.0.
```

Figure 13 : Routed flow from a plot unit

5.0 RESULTS

The rainfall excess occured at the end sub-plot of A2 plane and the routed flow reaching the channel is shown in Fig. 13. A double peak in the routed flow can be seen.

The cause of double peak is attributed to the catchment characteristic than the rainfall which shows only one peak. The table below shows the occurrence of peak rainfall at various sub-plots.

TABLE 5 : OCCURENCE OF PEAK

Sub-Plot	Peak of rainfall excess (Min.)
1	160
2	160
3	140
4	140
5	140
6	140
7	140
8	140
9	140
10	120

The variation in the time of occurrence of peak of rainfall excess is the chief reason for the double peak. This in turn is caused by varying infiltration at different sub-plots.

The routed flow at the outlet is shown in figure 14. The computed hydrograph nearly metches that of Ross et al, who used Finite Element method of analysis.

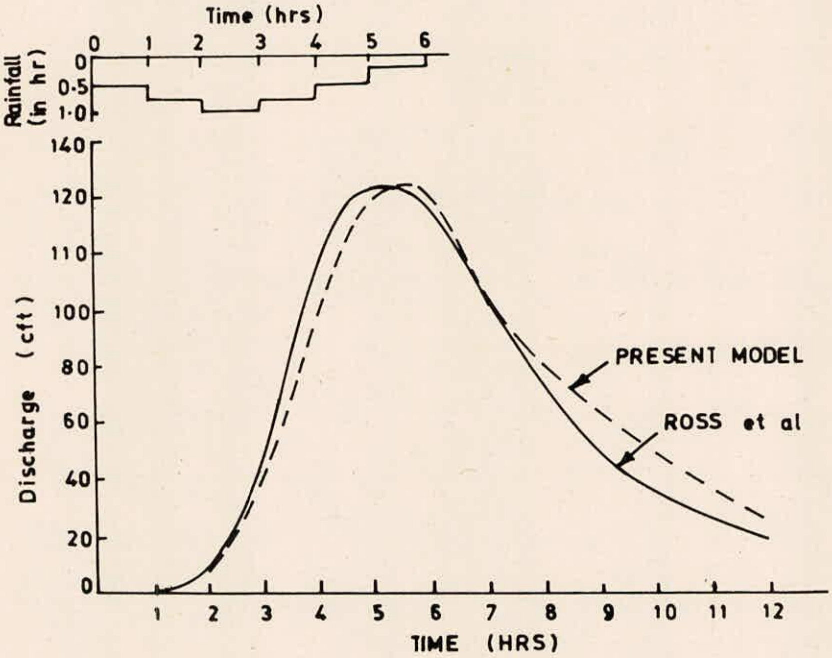


Figure 14 : Comparison of hydrographs of present computation and that of Ross

6.0 CONCLUSION

Dividing the watershed into sub-plots is the common feature seen in all distributed models used for overland flow. It is usual to go in for kinematic approximation.

Soil model which computes the rainfall excess using certain infiltration equation is an important component. The use of Holtan's equation is convenient in the model.

The chief problem in any watershed is its hetrogenity and the difficulty in identifying homogeneous units.

For the solution of the gradually varied flow equations, numerical methods like finite difference, finite element and method of characteristics are used. The comparison between different schemes revealed that shortcomings are present in each of the methods as explained in Appendix I & II. The familiarity of the modeller is the main reason for the selection of a particular method. Considerable research on the numerical techniques need to be done before a practicable three dimensional model could be developed.

A numerical model is developed to take into account the land use characteristics while computing the overland flow as a hydrograph at a desired location. This divides the catchment into various units. Soil texture, initial moisture, land use can vary in each unit.The model uses Holton's infiltration equation to get rainfal excess. An explicit finite difference scheme is used to route the rainfall excess on plane surface.

The routed flow from the plane surface forms the lateral flow to channel wherein method of characteristics are used to route them to the outlet. Results are compared with that of Ross et al and found to be nearly matching.

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APPENDIX - I

METHODS OF CHARACTERISTICS

In the method of characteristics, the partial differential equations are converted into ordinary differential equation. This method has been used rather widely in overland flow (Liggett, 1975).

Formulations:

The continuity and momentum equations are as follows:

$$\frac{\partial y}{\partial t} + \frac{A}{B}\,\frac{\partial v}{\partial x} + v\,\frac{\partial y}{\partial x} = q \qquad \ldots (1)$$

$$g\,\frac{\partial y}{\partial x} + \frac{\partial v}{\partial t} + v\,\frac{\partial v}{\partial x} = g\,(S_o - S_f) - \frac{qv}{A} \qquad \ldots (2)$$

Multiplying the continuity equation by ± CB/A, adding it to the momentum equations and then rearranging the terms, the characteristic equations are obtained:

$$\left[\frac{\partial v}{\partial t} + (v + c)\,\frac{\partial v}{\partial x}\right] + \frac{g}{c}\left[\frac{\partial y}{\partial t} + (V + c)\,\frac{\partial y}{\partial x}\right] = \frac{q}{A}\,(c-v) + g(S_o - S_f) \qquad \ldots(3)$$

$$\left[\frac{\partial v}{\partial t} + (v - c)\,\frac{\partial v}{\partial x}\right] - \frac{g}{c}\left[\frac{\partial y}{\partial t} + (v - c)\,\frac{\partial y}{\partial x}\right] = \frac{-q}{A}\,(c-v) + g(S_o - S_f) \qquad \ldots(4)$$

The above equations (3) and (4) can be converted to ordinary differential equations by defining the following equations (5) and (6) respectively:

$$\frac{dx}{dt} = v + c \qquad \ldots (5)$$

$$\frac{dx}{dt} = v - c \qquad \ldots (6)$$

The equations (3) and (5) represent positive characteristic equations. Whereas the equations (4) and (6) represent negative characteristic equations.

Refering to the figure 1 and using equations (5) and (6) the following can be deduced:

$$LP = DT\ (U_M + C_M + U_L + C_L)/2 \qquad \ldots (7)$$

$$PR = -DT\ (U_M - C_M + U_R - C_R)/2 \qquad \ldots (8)$$

The equation (3) can be written in its finite difference from between the discrete points L, M, and P:

$$\left[\frac{V_M - V_P}{DT} + (V_L + C_L)\ \frac{(V_P - V_L)}{LP}\right]$$

$$+ \frac{g}{C_L}\ \left[\frac{Y_M - Y_P}{DT} + (V_L + C_L)\ \frac{(Y_P + Y_L)}{LP}\right]$$

$$= \frac{q_L}{A_L}\ (C_L - V_L) + g\ (S_o - S_{fLM}) \qquad \ldots (9)$$

By definition the following are made for convenience of writing the equation:

$$ULCL = U_L + C_L \qquad \ldots (10)$$

$$GCL = g/C_L \qquad \ldots (11)$$

$$QTL = (q/A_L)\ DT\ (C_L - U_L) \qquad \ldots (12)$$

$$DTGL = g(DT\ (S_o - S_{fLM}) \qquad \ldots (13)$$

$$UDXL = -(DT/LP)\ (ULCL)\ (U_P - U_L) \qquad \ldots (14)$$

$$YDXL = GCL\ (Y_P - ULCL\ (DTC(Y_P - Y_L)))/LP \qquad \ldots (15)$$

$$RHL = V_P + UDXL + YDXL + QTL + DTGL \qquad \ldots (16)$$

$$V_M = RHL - GCL\ (Y_M) \qquad \ldots (17)$$

Similarly the equation (4) can be written in its finite difference form between the discrete points R, P and M.

$$\left[\frac{V_M - V_P}{DT} + (V_R - C_R)\ \frac{V_R - V_P)}{PR}\right]$$

$$- \frac{g}{C_R}\left[\frac{Y_M - Y_P}{DT} + (V_R - C_R)\ \frac{(Y_R - Y_P)}{PR}\right]$$

$$= \frac{-q_R}{A_R}\ (C_R - V_R) + g\ (S_o - S_{fRM}) \qquad \ldots (18)$$

For convenience, the following are defined:

$URCR = V_R - C_R$ ... (19)

$GCR = g/C_r$ ... (20)

$QTR = DT\ (q_R/A_R)\ (V_R - C_R)$ ... (21)

$DTGR = DT\ (g\ (S_o - S_{fRM}))$ ... (22)

$UDXR = URCR\ (DT\ (V_P - V_R))/PR$ ... (23)

$YDXR = GCR\ (-Y_P + URCR\ (DT\ (Y_R - Y_P))/PR$ ... (24)

$RHR = V_P + UDXR + YDXR + QTR + DTGR$ ... (25)

$V_M = RHR + GCR\ (Y_M)$ ... (26)

Solving equation (17) and (26), the following can be obtained:

$Y_M = (RHR - RHL)\ /\ (GCR + GCL)$ ... (27)

Substituting this in either equations (17) or (26), V_M can be found.

This is an explicit method since the derivatives of the St. Venant equations are approximated by the known conditions at the beginning of the time step. There are other schemes in the explicit formulation, that can be made in addition to the above. Most commonly known are (1) two step Lax-Wendroff scheme and Dronker's scheme. The former can be seen in Lax et al (1960) and Dronker (1965) for the latter.

The finite difference scheme presented above is stable only if the following inequality of Courant, et al (1928) is satisfied.

$$\Delta t \leq \frac{\Delta x}{V \pm C}$$

This is called Courant-Friendrichs-Lewy condition.

Computational Procedure :

A channel is divided into (n-1) reaches:

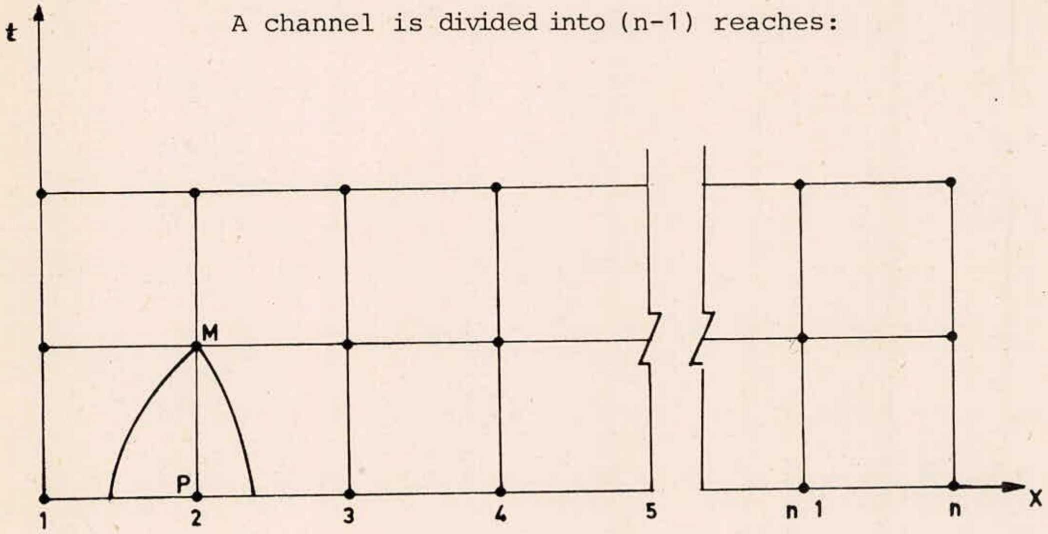

Fig. 1/I: Space time grid with (n-1) Reacher of the channel

The points L, R are fixed using equations (7) and (8). The conditions at L,R are interpolated using known conditions at section 1, 2, 3. Further using equations (27) and (28), the conditions at M are computed. Similarly the computations proceed upto n sections, before stepping up the time step. This procedure is continued until the transient conditions for the required time are computed. It should be ensured that Courant stability condition is satisfied at all the stages of computation. If it is not satisfied the time step is reduced.

Inidial conditions:

The initial flow depth and velocity should beknown.

These conditions should be compatible, otherwise artificial disturbance may mask the actual solution. A constant depth and zero velocity can be assumed. The initial steady state condition is then imposed at the boundary. Computations may be carried out for a sufficiently long time until the variation of flow conditions is small. This condition can be taken as initial condition.

Another way of finding them is to compute water surface profile using any of the step methods (Henderson, 1966).

Implicit methods are some times used in place of explicit methods. One advantage is that they are unconditionally stable. But results in matrix equations requiring complex solution procedure than explicit methods. Application of implicit methods can be seen in Amein, et al (1970), Vasitiev, (1965). A comparison of explicit method and implicit can be seen in Table 1.

No	Explicit	Implicit
	STABILITY	
1.	Stable only when Courant condition is satisfied	No such restrictions
	EASE OF PROGRAMMING	
2.	Easier to programme	Comparitively difficult
	ECONOMY	
3.	Economy differ problem to problem. Largely depend on the time step Δt choosen.	Although the time step Δt has no restriction. On stability criteria problem needs restrict them. This together with the solution of complex algebriaic system may turn to be costly.

	COMPUTER MEMORY REQUIREMENT	
4.	No matrix need to be formed. Hence memory need are minimal.	Depending on the problem large matrices need to be formed and solved. This demand large computer memory.
5.	Sharp peaks. Since Smaller Δt are used explicit methods are suitable for analysis of unsteady flow with sharp peaks of short duration. The sharp peaks can be reproduced.	Larger peaks may be missed in simulation
6.	Physical meaning. The difference scheme adopted can be physically explained.	There is no explanation as to why any variable need to be dependent on different conditions exist on other points in x-t plane
	ARTIFICIAL COEFFICIENT	
7.	No such coefficient is used.	Weighting coefficient Q, $0 < Q \leq 1$ is introduced to aid numerical solution.

APPENDIX - II

A COMPARISON OF FEM AND FDM IN SURFACE WATER

INTRODUCTION

In practice, physical processes are expressed in the form of laws and concepts based on the understanding of the nature. Such laws and concepts are translated to mathematical expressions for the purpose of analysis. For example conservation of mass is expressed as continuity equation in the case of fluid flows. Often, partial differential equations in our analysis. Many times analytical solution to these are not at all possible for a given boundary condition. Hence one has to resort to numerical techniques. The Finite Difference Methods (FDM) and the Finite Element Methods (FEM) are the two major class of the above techniques of wide use. The engineers faced with a question of choice between these two have to understand the relative merits of each one. Therefore, the following are aimed at bringing in the differences and the similarity of these two as found in the literature especially in the point of view of a surface water hydrologist.

It is reasonable to think that both FDM and FEM are related and similar, since they are expected to arrive at an approximate solution to the problem, of course from two different directions. FDM approximates differential equations by a difference approach whereas FEM does it by an integral approach. It is interesting to note that integration and differentiation are inverse to each other.

The proven strength of FEM is its ability to accommodate curved boundaries and non-homogeneous material properties over FDM.

However, these differences are not of serious considerations as far surface water analysis are concerned. Two important practical considerations are: (1) Accuracy wherein how best the solutions represents the true solution is considered; (2) Efficiency as a measure of computational efforts to obtain the solution. They are discussed below:

Accuracy Consideration:

A general statement 'the Finite Element Method' has been applied successfully to the shallow water wave equation', can be found in many research papers. Analysing number of surface water FEM models W.G. Gray (1980) found that excessive numerical damping is the common shortcoming of these model. The models he considered include Grotkop (1975); Tayler and Davis model (1975); Southampton models; CAFE model; Linch and Gray (1978); Kawahara and Masuda models (1978 & 1979); Neimeyer model (1979); RMA model. Most of these models employed physically unrealistic friction factor to tune the model to a given problem. These excessive friction through damping produced smooth solutions.

Propagation characteristics of numerical schemes have been studied by Gray, W.G. and Pinder, G.F. (1976) using one dimensional convective diffusion equation:

$$\frac{\partial c}{\partial t} + U\frac{\partial c}{\partial x} - D\frac{\partial^2 c}{\partial x^2} = 0 \qquad \dots (1)$$

where,

c is concentation (mg./L^3)

U is constant average velocity (L/T)

D is constant dispersion coefficient (L^2/T)

Both FEM and FDM exhibit problems of numerical dispersion and dissipation. Numerical dispersion produces oscillations in the computed solution and are caused by phase difference between the computed and true solutions. Numerical dissipation produces smeared out solutions and are caused by amplitude difference between true and computed solutions.

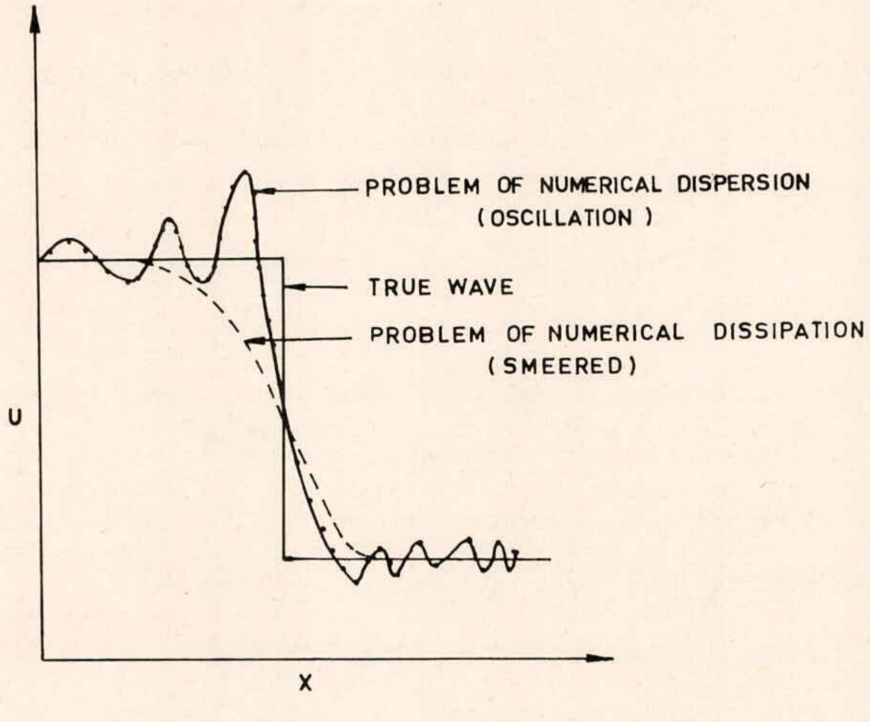

Figure 1/II Oscillatary and damped solutions

The Fig.1 illustrates these problems. A comparitive examination suggest that FEM aresuperior. Investigating on to the superiority of this method it is found that while phase lag (Numerical disperision) is common to both FEM and FDM in the case of short wave length components of the solution which are not truely propagated, whereas FDM amplifies these short wave length. Components thereby producing spurious oscillations. It is desirable to dampen the components which could not be propagated at true speed.

In the case of FDM arbitrary weighting factors are used to improve the solution.

With these factors one has a choice either to have a oscillatory or highly smeared solution. It may be noted that these factors do not have any physical meaning.

At the end of their discussions Zienkiewicz, O.C. Gallagher, R.H., and Hood (1975) compared FDM and FEM. They observed that flow slow flows where convective terms are insignificant FEM is found to be superior. With high velocities when convective terms become important and in transient problems the FDM retains some apparent superiority. For making this comparison they have used Galerkin FEM. An important observation upon this formulation is worth noting at this stage. It has been observed by Palaniappan (1980) that Galerkin method produces physically unrealistic solutions like negative concentrations while solving convective diffusion equation. Similar observations were also made by Gaertner (1976) who found sub domain collocation methods (a sub class of FEM) are superior for the above problem.

In an analysis, Gray and Pinder (1976) found that while most finite difference schemes produce an accuracy of the solution which is the same at all nodes, the finite element scheme the accuracy differed from one type to the other. Solutions at the corner nodes are 4th order correct while midside nodes are 2nd order correct. When quadratic shape functions are used. The addition of midside nodes however increases the accuracy of the solutions at corner nodes.

Efficiency

The finite element methods need greater care in discretization and node numeering. The fig. 2a and fig. 2b shows two different pattern of discretization, but with same number of nodes. It is found that the pattern 2b produces better solution than the other (Huyakorn et .al 1978). Because of this quality FEM requires intution to apply effectively to a given problem unlike FDM. Refinement of grid leads to larger computational effort than coarser approximations.

Fig. 2/II Twodifferent discretization

Discussing on the question finite element or finite difference methods for the two dimensional shallow water equations Weare, (1976) found unit cost (per node per time step) increases with band width in the case of FEM whereas in FDM the unit cost is independent of the overall size of the model. If 'i' iterations are necessary per time step while using Gauss elemination the number of operations involved in matrix solution is:

$i \times 2 \times (3n) \times (3m)/n = 18$ mi/node/time step where, 3n is the matrix size, 3m is semi band width and n is total number of nodes. In the case of Crank-Nicolsion the same is:

$(\frac{27}{m^2} + 18\ m)$ per node and per time step.

Matrix techniques are not generally required in explicit FDM. For ICL computer FDM required 40 units of work (5 multiplication) per grid point per time step. The relatively low efficiency of FEM stems from the sparseness of global matrix. The banded matrix is found to contain many zeros within it. This does not lead to any computational simplification in Gauss elemination. However, since the accuracy of FEM are greater than FDM, it can be expected coarser discretization would be sufficient for a problem. If FEM is to compete with FDM in the computational efforts (weare (1976)) FEM must satisfy the following inequality.

$mi < 4$ (for explicit interative scheme)

where, m is the largest difference of adjacent nodes and i is the number of iteration per time step. It may be noted that i can at the best be equal to 2. But usually equals to 3 to 5. For implicit. scheme $m < 2$. Both these inequalities cannot be satisfied. Probably the only way out for FEM to be mdore viable is to go in for better matrix solution procedure. Recent development are towards this aim. Some can be seen in Iron (1970), Gopalkrishnan et al (1982).

APPENDIX-III COMPUTER PROGRAMMES

```
C     SOIL MOISTURE MODEL 1.1.1987
      DOUBLE PRECISION IMPLISIT A,Z
      COMMON /SOIL/DEX(300,2),QUL(300,3),PU(300),TI(300)
      DIMENSION PPT(20),QLAT(300),SID(2)
      DIMENSION CU(300)
      DATA SID/'RBS','LBS'/
      OPEN(UNIT=2,FILE='SOI.DAT',STATUS='OLD')
      OPEN(UNIT=3,FILE='SOI.RES',STATUS='NEW')
      READ(2,*),NPPT,DTP,DT,DLC,NCP
      READ(2,*)(PPT(I),I=1,NPPT)
      ILT=(DTP/DT)*NPPT
      PRIOD=NPPT*DTP
C     FOR NCP REACHS
C
      DO 600 ICP=1,NCP
C     INITIALISE
      DO 499 I=1,300
      DEX(I,1)=0.0
      DEX(I,2)=0.0
      QUL(I,ICP)=0.0
      QLAT(I)=0.0
 499  CONTINUE
C     FOR BOTH THE SIDES OF THE CHANNEL
C
      DO 400 IPI=1,2
C
      READ(2,*) NPLOT
C     FOR THE NUMBER OF PLUTS ON ONE SIDE OF THE CHANNEL
C
      DO 300 ITK=1,NPLOT
C
      READ(2,*) NHRU,W1,W2,DL,SO,GMN,NSEC,DX
      WRITE(3,1)
 1    FORMAT(1X,'A SOIL MOISTURE MODEL'/1X,21('*')/1X,52('-')/
      11X,'|',5X,'TIME',7X,'SOILV',5X,'INFIL',5X,
      2'RAIN',6X,'FLOW',1X,'|'/1X,52('-'))
      IL1=0
C     FOR THE NUMBER OF UNIT OF SAME HYDROLOGICAL RESPONSE IN INFILTRATION
C
      DO 20 IJK=1,NHRU
C
      TIME=0.0
C     AI AND PI ARE COEFICIENTS USED IN SOIL MODEL
C     SI IS AVAILABLE SOIL STORAGE CAUSING INFILTRATION
C     FIC IS THE CONSTANT INFILTRATION
C     P IS THE % OF AREA OF SAME CHARAECTERS
C     F IS THE INFILTRATION COMPUTED
      READ(2,*)AI,SI,PI,FIC,P
      IL=0
 77   TIME=TIME+DT
      IL=IL+1
      NT=(TIME-5.)/DTP +1
      PRE=PPT(NT)
      F=AI*(SI**PI)+FIC
      IF(F.LT.FIC)F=FIC
      IF(F.GT.PRE)F=PRE
C     QP IS THE PRECIPITATION EXESS
      QP=PRE-F
      QLAT(IL)=QLAT(IL)+QP*P*DT/720.
      ITL=TIME/60.
      IF(ITL*60.EQ.TIME)WRITE(3,11) TIME,SI,F,PRE,QP
 11   FORMAT(1X,'| ',F9.2,4F10.3,' |')
      SI=SI-F*DT/60.
      IF(SI.LT.0.0)SI=0.0
      IF(TIME.LT.PRIOD) GO TO 77
```

```
      WRITE(3,111)
      IF(IL1.GT.IL)IL=IL1
      IL1=IL
 20   CONTINUE
 111  FORMAT(1X,52('-'))
      WRITE(3,2) (QLAT(I),I=1,IL)
      IPK=0
      DO 39 IYH=12,300,12
      IPK=IPK+1
39    PU(IPK)=QLAT(IYH)
 2    FORMAT(1X,'DEPTH OF RAINFALL EXESS FOR EVERY DT min IN (ft) :'/
      11X,20(F5.3,1X)/1X,20(F5.3,1X)/1X,20(F5.3,1X))
      SBN=1.486*(SO**.5)/GMN
      DO 100 IR=1,300
      TI(IR)=IR
C     W1 AND W2 ARE FOR LINKING PLOTS
 100  DEX(IR,IPI)=DEX(IR,IPI)*W1/W2 +QLAT(IR)
      WRITE(3,33) ITK,SID(IPI)
 33   FORMAT(1X,' THE PLOT NO.',I5,' OF ',A3//)
      WRITE(3,22)
 22   FORMAT(1X,82('-')/1X,'|',1X,'TIME',11X,'SITE 1',14X,'SITE 2',9X
      1,'QLATERAL',2X,'DQ/DX',5X,'YEND',5X,'|'/1X,'|',12X,'Yexess',5X
      2,'Q1',8X,'Yflow',5X,'Q2',26X,'of DT',4X,'|'/1X,'|',' (min)',5X
      3,'(ft)',3X,'(cuft/DT/ft)',1x,'(ft)',3x,'(cuft/DT/ft)',3X,'(ft)'
      4,4x,'(ft)',5x,'(ft)',6x,'|'/1x,'|',80('-'),'|')
      DO 200  IJK=1,NSEC
      TIME=0.0
      WRITE(3,3) IJK
 3    FORMAT(1X,'|',2X,'SECTION NO. ',6X,I5,55X,'|')
      YEND=0.0
      IMK=0
      QP1=0.0
      QP2=0.0
      QLL=0.0
 88   IMK=IMK+1
      IF(IMK.GT.300) GO TO 200
      TIME=TIME+DT
      YEX=DEX(IMK,IPI)
      Q1=SBN*(YEX**1.6666)
      Q=(QP1+Q1)/2.
      QP1=Q1
      Q1=Q*DT*60.
      DFLO=YEND+QLAT(IMK)
      Q2=SBN*(DFLO**1.6666)
      Q=(QP2+Q2)/2.
      QP2=Q2
      Q2=Q*DT*60.
      QL1=QLAT(IMK)
      QL=(QL1+QLL)/2.
      QLL=QL1
      DQDX=(Q2-Q1)/DX
      YEND=QL+YEND-DQDX
      IF(YEND.LT.0.0)YEND=0.0
      IF((IMK/12)*12.EQ.IMK)WRITE(3,222)TIME,YEX,Q1,DFLO,Q2,QL
      1,DQDX,YEND
      DEX(IMK,IPI)=YEND+QLAT(IMK)
      IMK1=IMK/12

      IF(IMK1*12.NE.IMK)GO TO 66
      CU(IMK1)=YEND
C     PU(IMK1)=QL1
 66   IF(IMK.LE.IL) GO TO 88
      IF(YEND.GT..005) GO TO 88
      WRITE(3,2222)
 2222 FORMAT(1X,82('-'))
```

```
 200    CONTINUE
C       CALL PLOT(PU,TI,40,CU)
        DO 199 IBG=1,40
 199    CU(IBG)=0.0
 300    CONTINUE
        PP=W2/DLC
        DO 399 I=1,300
 399    QUL(I,ICP)=PP*SBN*(DEX(I,IPI)**1.6666)+QUL(I,ICP)
 400    CONTINUE
 600    CONTINUE
        CALL CHANNEL(DT)
 222    FORMAT(1X,'|',1X,F9.2,5(F9.4,1X),F9.6,1X,F9.4,1X,'|')
        STOP
        END
        SUBROUTINE PLOT (QLAT,TIME,N,CU)
        DIMENSION TIME(300),QLAT(300),A(101),CU(300)
        DATA CHAR,GRID,BLANK,ZERO/1H*,1H+,1H ,1H0/
        QMAX=CU(1)
        CUMAX=QLAT(1)
        DO 10 I=1,N
        IF(CUMAX-QLAT(I))11,9,9
11      CUMAX=QLAT(I)
9       IF(QMAX-CU(I))8,10,10
8       QMAX=CU(I)
10      CONTINUE
        CUMAX=AMAX1(CUMAX,QMAX)
        SF=CUMAX/50.
        DO 12 I=1,51
12      A(I)='-'
        WRITE(32,13)(J,J=1,51,10)
13      FORMAT(/2X,'TIME',5X,I2,5(6X,I4),4X,'PPT.',5X,'  Qrun'/)
        NA=(CUMAX-QLAT(1))/SF+1.5
        NB=CU(1)/SF+1.5
        I=1
        A(NA)=CHAR
        A(NB)=ZERO
        WRITE(32,14)TIME(I),(A(J),J=1,51),QLAT(I),CU(I)
14      FORMAT(1X,F6.1,5X,51A1,F9.3,F9.2)
        DO 15 I=1,51
15      A(I)=BLANK
        K=1
        KC=7
        DO 20 I=2,N
        KN=TIME(I)-TIME(I-1)
        AA=(CUMAX-QLAT(I))/SF+1.5
        NB=CU(I)/SF+1.5
        NA=AA
22      DO 21 I1=1,51,10
21      A(I1)='|'
        IF(KC-KN-K)24,25,26
24      KP=KC-K
        IF(KP-1)30,30,34
34      DO 31 J=2,KP
31      WRITE(32,91)(A(JJ),JJ=1,51)
91      FORMAT(12X,51A1)
30      DO 32 J=1,51
32      A(J)=GRID
        WRITE(32,92)(A(JJ),JJ=1,51)
92      FORMAT(12X,51A1)
        DO 33 J=1,51
33      A(J)=BLANK
        KN=KN-KC+K
        K=KC
        KC=KC+6
        GO TO 22
```

```
25    IF(KN-1) 40,40,41
41    DO 42 J=2,KN
42    WRITE(32,91)(A(J1),J1=1,51)
40    DO 43 J=1,51
43    A(J)='-'
      A(1)='+'
      A(11)='+'
      A(21)='+'
      A(31)='+'
      A(41)='+'
      A(51)='+'
      A(NA)=CHAR
      A(NB)=ZERO
      WRITE(32,14)TIME(I),(A(J),J=1,51),QLAT(I),CU(I)
      K=KC
      KC=KC+6
      GO TO 27
26    IF(KN-1)50,50,51
51    DO 52 J=2,KN
52    WRITE(32,91)(A(JJ),JJ=1,51)
50    A(NA)=CHAR
      A(NB)=ZERO
      K=K+KN
      WRITE(32,14)TIME(I),(A(J),J=1,51),QLAT(I),CU(I)
27    DO 28 J=1,51
28    A(J)=BLANK
20    CONTINUE
      KP=KC-K
      IF(KP-1) 60,60,61
 61   DO 62 J=1,51,10
62    A(J)=GRID
      DO 63 J=2,KP
63    WRITE(32,91)(A(JJ),JJ=1,51)
60    DO 64 J=1,51
64    A(J)=GRID
      WRITE(32,91)(A(JJ),JJ=1,51)
      WRITE(32,13)(J,J=1,51,10)
C     WRITE(32,95)SF
95    FORMAT(1X,'THIS GRAPH HAS A SENSITIVITY OF',E10.3,'UNITS/SPAC
      1ING IN THE HORIZONTAL AXIS')
      WRITE(32,96)KC
96    FORMAT(1X,'SENSITIVITY IN THE VERTICAL AXIS IS 1.00 UNITS/LINE
      1'//1X,'TOTAL NUMBER OF LINES IS ',I4,'IN THIS PLOT')
      RETURN
      END
```

```
      SUBROUTINE CHANNEL (HY)
      REAL*8 SO,SF1,SF2,SFZ,SFL,SFR,SFM
      COMMON UP(50),DL(50),HP(50),W(50),DC(50),DX,QI,SO,WP(50),DIS(3)
      COMMON/INDEX/NSEC,DT,DTH,GMN,IPRI,UNIT,G
      COMMON/FLO/RN(50),UQ(300)
      COMMON /FRIC/RL,RR,RP,UL,UR,HL,HR,AL,AR
      COMMON /SOIL/DEX(300,2),QUL(300,3),PU(300),TI(300)
      DIMENSION CU(300),HPP(50),UPP(50)
      DATA NHYD/100/
      DTH=HY
      CALL DATAIN
398   FORMAT(1X,'No ','SFL'7X,'SFR',7X,'SFM',17X,'UP...1...8')
467   FORMAT(6X,'RL/R',11X,'RL/R1',10X,'UDXL/R',9X,'YDXL/R',9X,'QTL/R',
      110X,'DTGL/R',9X,'RHL/R',10X,'GCL/R')
      DT=DT*60.
      DTH=DTH*60.
      T1=DTH*(NHYD-1)
      NT1=(T1-1.)/DT +1
      WRITE(9,1)T1,DT,NT1
1     FORMAT(1X,'The time base of the hydrograph is ',F10.1,
      1'sec.',/1X,'The number of iterations at DT = ',F7.1,
      21X,' are ',I10)
      WRITE(9,2)(DL(I),I=1,NSEC)
2     FORMAT(1X,'SEC. AT',10X,11F9.1)
      W1=W(1)
      W2=WP(1)
      S1=DC(1)
      ICP=1
      DO 3 I=1,NHYD
      YN=0.0
      QO=QUL(I,ICP)
      IF(QO.LE.0) GO TO 3
      YN=S1
      CALL NORMAL(QO,GMN,SO,YN,W1,W2)
3     UQ(I)=YN
      WRITE(9,29)(UQ(I),I=1,NHYD)
      DHP=HP(1)
29    FORMAT(1X,'UQ ',10F10.6)
      MIT=0
      DO 1000 IDH=1,NT1
      X=0.0
      TIME=DT*IDH
      XM=TIME/DTH +.9999
      M=XM
11    FORMAT(1X,'Time ',95X,F8.0,1X,F10.2)
      SI=(TIME-(M-1)*DTH)*(UQ(M+1)-UQ(M))/DTH +UQ(M)
      SI=SI+DHP
      IME=TIME
      IM1=(TIME-1.)/60. +1
      W1=W(1)
      W2=WP(1)
      S1=DC(1)
      QI=0.0
      ICP=1
      CALL RA(W1,W2,SI,S1,A1,R1)
      QI=(SO**.5)*A1*GMN*R1**.6666
      IF((IME/IPRI)*IPRI.NE.IME)GO TO 44
      MIT=MIT+1
      TI(MIT)=MIT
      WRITE(9,11)TIME,QI
44    VEL=QI/A1
      UP(1)=VEL
      HP(1)=SI
      UPP(1)=UP(1)
      HPP(1)=HP(1)
```

```
C
      DO 900 ISE=2,NSEC
      ITE=0
      X=DL(ISE)
      IF(DL(ISE).GT.DIS(1).AND.DL(ISE).LE.DIS(2))ICP=2
      IF(DL(ISE).GT.DIS(2).AND.DL(ISE).LE.DIS(3))ICP=3
      QT=(TIME-(M-1)*DTH)*(QUL(M+1,ICP)-QUL(M+1,ICP))/DTH +QUL(M,ICP)
      YR=HP(ISE)
      YL=YR
      VELR=UP(ISE)
      VELL=VELR
 111  ITE=ITE+1
      IF(ITE.GT.20) GOTO 999
      GYL=(G*YL)**.5
      GYR=(G*YR)**.5
      VZ=(VELL+GYL)*DT
      VY=(VELR-GYR)*DT
      XL=X-(VELL+GYL)*DT
      XR=X-(VELR-GYR)*DT
      CALL GEOM(XL,XR,ISE,ITE)
      CALL PALANI(UM,HM,ISE,QT,XL,XR)
      IF(HM.LT.0.0) HM=0.0
C     YL=(HM+HL)/2.
      YL=HL
C     VELL=(UM+UL)/2.
      VELL=UL
C     YR=(HM+HR)/2.
      YR=HR
C     VELR=(UM+UR)/2.
      VELR=UR
      IF(ITE.EQ.1)GO TO 888
      IF(ABS((UM-UPP(ISE))/UM).LE..05) GO TO 222
 888  HPP(ISE)=HM
      UPP(ISE)=UM
      GO TO 111
 222  IF(UM.LT.0.0) UM=0.0
      HPP(ISE)=HM
      UPP(ISE)=UM
 900  CONTINUE
      DO 998 IU=1,NSEC
      HP(IU)=HPP(IU)
 998  UP(IU)=UPP(IU)
      IF((IME/IPRI)*IPRI.NE.IME)GO TO 1000
      WRITE(9,22)(HP(I),I=1,NSEC),(UP(J),J=1,NSEC)
      CU(MIT)=HM
      PU(MIT)=SI
 22   FORMAT(1X,'Depth',7F10.5/1X,'Velo.',7F10.5)
 1000 CONTINUE
      WRITE(32,33)
 33   FORMAT(1X,'THIS PLOT SHOWS THE RAINFALL EXCESS AND THE ROUTED'
      1,1X,'FLOW'/)
      TYPE*,'MIT',MIT
      CALL PLOT(PU,TI,MIT,CU)
      RETURN
 999  WRITE(9,1111)
 1111 FORMAT(1X,'The iterations are more')
      RETURN
      END
      SUBROUTINE DATAIN
      REAL*8 SO,SF1,SF2,SFZ,SFL,SFR,SFM
      COMMON UP(50),DL(50),HP(50),W(50),DC(50),DX,QI,SO,WP(50),DIS(3)
      COMMON/INDEX/NSEC,DT,DTH,GMN,IPRI,UNIT,G
      COMMON/FLO/RN(50),UQ(300)
      SO=0.0
      READ(2,*) NSEC,DX,DT,GMN,SO,IPRI,UNIT,G
```

```
        READ(2,*) (DL(I),I=1,NSEC)
        READ(2,*) (W(I),I=1,NSEC)
        READ(2,*)(WP(I),I=1,NSEC)
        READ(2,*)(HP(I),I=1,NSEC)
        READ(2,*)(DC(I),I=1,NSEC)
        READ(2,*)(DIS(I),I=1,3)
        GMN=UNIT/GMN
        R1=W(1)*HP(1)/(W(1)+2.*HP(1))
        R2=R1**.6666
        VEL=SQRT(S0)*GMN*R2
        SFZ=VEL/(GMN*R2)
        SFZ=SFZ*SFZ
 19     FORMAT(1X,'IN THE DATAIN THE Hyd.dep :'F10.6/1X,'THE 2/3',19X,
        1':',F10.6/1X,'THE INITAL VELOCITY : ',F15.10)
 29     FORMAT(1X,'IN DATAIN THE ENERGY SLOPE BACK CALCULATION ',F15.12)
        DO 10 I=1,NSEC
 10     UP(I)=VEL
        RETURN
        END
        SUBROUTINE RA(W1,W2,SI,DC,A,R)
        IF(SI.LE.DC) GO TO77
        A=DC*W1+(SI-DC)*W2
        P=W2+2.*SI
        GO TO 66
 77     A=SI*W1
        P=W1+2.*SI
 66     R=A/P
        RETURN
        END
        SUBROUTINE PALANI(UM,HM,ISE,QT,XL,XR)
        REAL*8 S0,SF1,SF2,SFZ,SFL,SFR,SFM
        COMMON UP(50),DL(50),HP(50),W(50),DC(50),DX,QI,S0,WP(50),DIS(3)
        COMMON /INDEX/NSEC,DT,DTH,GMN,IPRI,UNIT,G
        COMMON /FRIC/RL,RR,RP,UL,UR,HL,HR,AL,AR
        COMMON /FLO/RN(50),UQ(300)
        RP1=RP**.6666
        RL1=RL**.6666
        RR1=RR**.6666
C       WRITE(51,19)RP,RL,RR,RP1,RL1,RR1
 19     FORMAT(1X,'THE HYDRAULIC DEPTH RP RL RR RESPTY : ',3F10.6,
        1/1X      'THE 2/3 POWER OF ABOVE                : ',3F10.6)
        SFM=UP(ISE)/(GMN*RP1)
C       WRITE(51,29)ISE,UP(ISE),SFM,S0
 29     FORMAT(1X,'AT THE SECTION ',I5,' VEL & Sf ARE  : ',3F14.12)
        SFM=SFM*SFM
        SFL=UL/(GMN*RL1)
C       WRITE(51,29)ISE,UL,SFL,S0
        SFL=SFL*SFL
        SF1=(SFL+SFM)/2.
        SFR=UR/(GMN*RR1)
C       WRITE(51,29)ISE,UR,SFR,S0
        SFR=SFR*SFR
        SF2=(SFR+SFM)/2.
C       WRITE(51,129)SFL,SFR,SF1,SF2
 129    FORMAT(1X,'THE ENERGY SLOPE',20X,F14.10/37X,F14.10/37X,F14.10)
        CL=(G*HL)**0.5
        CR=(G*HR)**0.5
C       WRITE(51,39) CL,CR
 39     FORMAT(1X,'THE CELARITY AT THE LEFT & RIGHT ARE : ',2F14.10)
        QTL=DT*QT*(CL-UL)/AL
        QTR=DT*QT*(UL-CL)/AR
C       WRITE(51,49)QTL,QTR
 49     FORMAT(1X,'TERM FOR LATERAL FLOW L&R ',2F14.10)
        DTGL=DT*G*(S0-SF1)
        DTGR=DT*G*(S0-SF2)
```

```
C       WRITE(51,59)DTGL,DTGR
 59     FORMAT(1X,'THE BALANCE OF GRAVITY & FRICTION ',2F15.10)
        GCL=G/CL
        GCR=G/CR
C       WRITE(51,69)GCL,GCR
 69     FORMAT(1X,'THE RATIO OF GRAVITY TO CELERITY L&R ',2F15.10)
        YDXL=GCL*(HP(ISE)-DT*(UL+CL)*(HP(ISE)-HL)/XL)
        YDXR=GCR*(-HP(ISE)+DT*(UR-CR)*(HR-HP(ISE))/XR)
C       WRITE(51,79)HP(ISE),HL,HR,YDXL,YDXR,CL,CR
 79     FORMAT(1X,'THE DEPTH AT P,L,R ARE : ',3F15.10/
        11X,      'THE YDXL,YDXR           : ',2F15.10/
        21X,      'THE EXPECTED VALUES ARE: ',2F15.10)
        DHR=DT*(UR-CR)*(HR-HP(ISE))/XR
        UDXL=UP(ISE)-DT*((UL+CL)*(UP(ISE)-UL)/XL)
        UDXR=UP(ISE)-DT*((UR-CR)*(UR-UP(ISE))/XR)
CC      WRITE(51,89)UDXL,UDXR,UP(ISE)
 89     FORMAT(1X,'THE VELOCITY TERMS & EXP. :',3F15.10)
        RHL=UDXL+YDXL+QTL+DTGL
        RHR=UDXR+YDXR+QTR+DTGR
C       WRITE(51,99)DHR
 99     FORMAT(1X,'THE DERIVATIVE OF DEPTH : ',F15.10)
C       WRITE(51,109)RHL,RHR
 109    FORMAT(1X,'THE RHL,RHR : ',2F15.8)
        HM=(-RHR+RHL)/(GCL+GCR)
        UM=RHR+GCR*HM
C       WRITE(51,119) HM,UM,HL,UL
 119    FORMAT(1X,'THE COMPUTED DEPTH,VELOCITY ARE : ',2F15.10/
        11X,      'THE EXPECTED VALUES ARE          : ',2F15.10)
        RETURN
        END
CC      SUBROUTINE MANING (GMN,QI)
C       DO 5 I=2,6
C C5    IF(QI.LE.QM(I))GO TO 10
C 10    GMN=GM(I-1)+(GM(I)-GM(I-1))*(QI-QM(I-1))/
C       1(QM(I)-QM(I-1))
C       RETURN
C       END
        SUBROUTINE GEOM(XL,XR,ISE,ITE)
        REAL*8 SO,SF1,SF2,SFZ,SFL,SFR,SFM
        COMMON UP(50),DL(50),HP(50),W(50),DC(50),DX,QI,SO,WP(50),DIS(3)
        COMMON /INDEX/NSEC,DT,DTH,GMN,IPRI,UNIT,G
        COMMON /FRIC/RL,RR,RP,UL,UR,HL,HR,AL,AR
        SL=1.0
        SR=1.
        DO 5 N=2,NSEC
 5      IF(XL.LE.DL(N))GO TO 7
        N=NSEC
 7      XD=XL-DL(N-1)
        IF(XD.LT.0)XD=0.
        XM=DL(N)-DL(N-1)
        IF(XD.GT.XM)XD=XM
        XD=XD/XM
        UL=UP(N-1)+XD*(UP(N)-UP(N-1))
        HL=HP(N-1)+XD*(HP(N)-HP(N-1))
        WL=W(N-1)+XD*(W(N)-W(N-1))
        AL=(WL*HL+HL*HL*(SL*SL-1.)**.5)
        RL=AL/(WL+2.*HL*SL)
        DO 6 N=2,NSEC
 6      IF(XR.LE.DL(N))GO TO 8
        N=NSEC
 8      XD=XR-DL(N-1)
        IF(XD.LT.0)XD=0.
        XM=DL(N)-DL(N-1)
        IF(XD.GT.XM)XD=XM
        XD=XD/XM
```

```
      UR=UP(N-1)+XD*(UP(N)-UP(N-1))
      HR=HP(N-1)+XD*(HP(N)-HP(N-1))
      WR=W(N-1)+XD*(W(N)-W(N-1))
      AR=WR*HR+HR*HR*(SR*SR-1.)**.5
      RR=AR/(WR+2.*HR*SR)
      AP=W(ISE)*HP(ISE)+HP(ISE)*HP(ISE)*(SL*SL-1.)**0.5
      RP=AP/(W(ISE)+2.*HP(ISE)*SL)
C     WRITE(61,19)RL,RR,RP
19    FORMAT(1X,'IN GEOM THE HYD.DEP. : ',3F10.6)
C     WRITE(61,29) HL,HR,AL,AR
 29   FORMAT(1X,'IN GEOM THE DEP.,AREA AT L&R ',4F14.10)
C     WRITE(61,39) UL,UR
 39   FORMAT(1X,'IN GEOM THE VELOCITY L&R ',2F15.10)
      RETURN
      END
      SUBROUTINE PLANI(UM,HM,ISE,QT,XL,XR)
      REAL*8 SO,SF1,SF2,SFZ,SFL,SFR,SFM
      COMMON UP(50),DL(50),HP(50),W(50),DC(50),DX,QI,SO,WP(50),DIS(3)
      COMMON /INDEX/NSEC,DT,DTH,GMN,IPRI,UNIT,G
      COMMON /FRIC/RL,RR,RP,UL,UR,HL,HR,AL,AR
      COMMON /FLO/RN(50),UQ(300)
C     WRITE(21,3) UM,HM,ISE,QT,XL,XR
 3    FORMAT(1X,'THIS IS TEST THE VALUES'/1X,'UM ',F10.6,' HM ',F10.6,
      1' ISE ',I5,1X,'QT ',F10.6,' XL ',F10.4,' XR ',F10.6)
      RP1=RP**.6666
      RL1=RL**.6666
      RR1=RR**.6666
C     WRITE(21,33)RP,RL,RR,RP1,RL1,RR1
 33   FORMAT(1X,'RP,RL,RR, ..**.6666) ',6F14.10)
      SFM=UP(ISE)/(GMN*RP1)
C     WRITE(21,46)SFM
 46   FORMAT(1X,'SF**2 M,L,R ',F14.10)
      SFM=SFM*SFM
      SFL=UL/(GMN*RL1)
C     WRITE(21,46)SFL
      SFL=SFL*SFL
      SF1=(SFL+SFM)/2.
      SFR=UR/(GMN*RR1)
C     WRITE(21,46)SFR
      SFR=SFR*SFR
      SF2=(SFR+SFM)/2.
CC    WRITE(21,333)UP(2),UL,UR,GMN,RP1,RL1,RR1,SFM,SFR,SF1,SF2,SO
333   FORMAT(1X,'UP(2),UL,UR,GMN,RP1,RL1,RR1,SFM,SFR,SF1,SF2'/
      11X,2F13.10,1X,5F13.10/1X,8F13.10)
      CL=(G*HL)**0.5
      CR=(G*HR)**0.5
C     WRITE(21,3333)G,HL,HR,CL,CR
 3333 FORMAT(1X,'G,HL,HR,CL,CR ',5F14.10)
      QTL=DT*QT*(CL-UL)/AL
      QTR=DT*QT*(UL-CL)/AR
      DTGL=DT*G*(SO-SF1)
      DTGR=DT*G*(SO-SF2)
C     WRITE(21,5)DT,QT,AL,AR,QTL,QTR,DTGL,DTGR
 5    FORMAT(1X,'DT,QT,AL,AR,QTL,QTR,DTGL,DTGR',F10.6,F14.12,1X,F14.10/1X,
      15F14.10)
      YDXL=(G/CL)*(HP(ISE)-DT*(UL+CL)*(HP(ISE)-HL)/XL)
      YDXR=(G/CR)*(-HP(ISE)+DT*(UR-CR)*(HR-HP(ISE))/XR)
C     WRITE(21,55) YDXL,YDXR
 55   FORMAT(1X,'YDXL,YDXR',2F14.10)
      GCR=G/CR
      DHR=DT*(UR-CR)*(HR-HP(ISE))/XR
      UDXL=UP(ISE)-DT*((UL+CL)*(UP(ISE)-UL)/XL)
      UDXR=UP(ISE)-DT*((UR-CR)*(UR-UP(ISE))/XR)
C     WRITE(21,555) UDXL,UDXR,DHR,GCR,GCL
 555  FORMAT(1X,'UDXL,UDXR,DHR,GCR,GCL',5F15.10)
```

```
      RHL=UDXL+YDXL+QTL+DTGL
      RHR=UDXR+GCR*(-HP(ISE)+DHR)+QTR+DTGR
C     WRITE(21,5555)UDXL,YDXL,QTL,DTGL,UDXR,QTR,DTGR,RHL,RHR
 5555 FORMAT(1X,'UDXL,YDXL,QTL,DTGL,UDXR,QTR,DTGR',7F14.10/
      11X,'RHL,RHR',10X,2F15.12)
      RTY=2.020908+(32.2*3.0)**.5
      RTZ=2.020908-(32.2*3.0)**.5
      UDT=UP(ISE)
      YDT=(32.2*3.)**.5
      GCL=G/CL
      GCR=G/CR
      GTZ=(32.2/3.)**.5
      HM=(-RHR+RHL)/(GCL+GCR)
      H1=(RTY-RTZ)/(2.*GTZ)
      UM=RHR+GCR*HM
      WRITE(21,6)HM,UM
      RS1=RHL-(UM+GCL*HM)
      RS2=RHR-(UM-GCR*HM)
 6    FORMAT(1X,'HM,UM ',2F15.10)
      U1=RTY-GTZ*H1
C     1,UDXR,YDXR,QTR,DTGR,RHR,GCR
 43   FORMAT(1X,8F15.8/)
 1    FORMAT(1X,'....SF1,SF2,DTG,UL,UR,HL,HR,C..',
      1F7.5,1X,F7.5,1X,F10.5,2X,2F10.4,1X,3F10.4)
C     WRITE(21,666) RS1,RS2
 666  FORMAT(1X,'RESIDUAL ERROS : ',2F15.10)
      MP=GCR/GCL
      UM1=(RHR+RHL*MP)/(1+MP)
      HM1=(RHL-UM1)/GCL
C     WRITE(21,66) HM1,UM1
66    FORMAT(1X,'HM,UM CALCULATED AS PER DIAGONAL DOMINANCE'/
      11X,7X,2F15.10)
      RS1=RHL-(UM1+GCL*HM1)
      RS2=RHR-(UM1-GCR*HM1)
C     WRITE(21,666) RS1,RS2
      RETURN
      END
      SUBROUTINE INTPOL (S1,Q,X,Y,N,H,I)
      DIMENSION Q(20,100)
      S= H
      DO 4 J=2,N-1
      S=S + H
 4    IF(S.GE.X) GO TO 3
      J=N-1
 3    PQ=(X-S)/H
      Y=Q(J,I)+(PQ/2.)*(Q(J+1,I)-Q(J-1,I)) +(PQ*PQ/2.)
      1*(Q(J+1,I)-2.*Q(J,I)+Q(J-1,I))
      RETURN
      END
      SUBROUTINE NORMAL(Q,GMN,S,YN,W1,W2)
      GES=YN
      IO=1
      SO=S**.5
      QP=SO*GMN*(W1*YN)*(W1*YN/(W1+2.*YN))**(2./3.)
      DC=YN
      YG=-.1
      YL=.1
      IF(QP.LT.Q)GO TO 20
 1    NEP=20
      DO 10 IP=1,1000
      YNP=YN
      YN=YN+YG
      IF(YN.LE.0)GO TO 50
C     CALL INTPOL(0.0,A,YN,AI,N1,DS,I)
C     CALL INTPOL(0.0,P,YN,PI,N1,DS,I)
```

```
      CALL RA (W1,W2,YN,DC,AI,R)
      QP=GMN*AI*(R**(2./3.))*S0
      IF(QP.LT.Q)GO TO 40
 10   CONTINUE
      GO TO 50
 20   NEP=1
      DO 30 NI=1,1000
      YNP=YN
      YN=YN+YL
C     CALL INTPOL(0.0,A,YN,AI,N1,DS,I)
C     CALL INTPOL(0.0,P,YN,PI,N1,DS,I)
      CALL RA (W1,W2,YN,DC,AI,R)
      QP=GMN*AI*(R**(2./3.))*S0
      IF(QP.GT.Q)GO TO 40
 30   CONTINUE
      GO TO 50
 40   IF(ABS(YL).LC..001) GO TO 60
      GES=YN
      YG=YG/10.
      YL=YL/10.
      IF(NEP.EQ.20) GO TO 20
      IF(NEP.EQ.1) GO TO 1
 60   YN=(YN+[illegible])/2
      RETURN
 50   IF(IO.EQ.2)GO TO 70
      IO=2
      YG=-YG
      YL=-YL
      YN=GES
      GO TO 1
 70   WRITE(3,6)
 6    FORMAT(1X,'THE NORMAL DEPTH IS NOT NEAR THE GUSS')
      RETURN
      END
```

APPENDIX-IV Input- Output

```
SOI.DAT;1                                   30-JUN-1987 10:40                    Page 1

 6 60. 10. 2200. 3
.5 .75 1. .75 .5 .25
2
2 0.0 550. 1000. .016 .388 5 200.
1.0 2.4 2.0 .14 .75
.75 3.0 1.1 .35 .25
3 550. 1650. 1000.  .01 .388 5 200.
1.0 1.2 2. .14 .7
1.0 1.5 2. .14 .05
.7 .75 1.1 .39 .15
2
2 0.0 2200. 750.  .016 .388 5 150.
1.0 2.2 2. .14 .7
.7 1.75 1.1 .39 .3
2 2200. 2200. 750.  .01 .388 5 150.
1.0 1.2 2. .14 .4
.7 2.75 1.1 .39 .6
2
2 0.0 2875. 1000. .012 .39 5 200.
1.0 2.4 2.0 .14 .9
.6 2.4 1.2 .12 .1
4 2875. 2425. 1000. .008 .353 5 200.
1.0 2.4 2.0 .14 .2
.6 2.4 1.2 .12 .15
.7 1.5 1.1 .39 .15
.7 2.0 1.1 .39 .5
2
3 0.0 3250. 750. .012 .355 5 150.
1.0 1.8 1.9 .14 .4
.6 2.4 1.2 .12 .3
.7 1.5 1.1 .39 .3
4 3250. 2550. 750. .008 .343 5 150.
1.0 1.8 1.9 .14 .1
.6 2.4 1.2 .12 .25
.7 1.5 1.1 .39 .25
.7 2.0 1.1 .39 .4
2
1 0.0 550. 1000. .008 .3 5 200.
.6 2.4 1.2 .12 1.
2 550. 1650. 1000. .005 .28 5 200.
.6 2.4 1.2 .12 .6
.5 .9 1.12 .01 .4
2
3 0.0 1975. 750. .008 .237 5 750
.6 2.4 1.2 .12 .2
.5 .9 1.12 .01 .7
0.0 0.0 1. 0.0 .1
3 1975. 2125 750. .005 .28 5 750.
.6 2.4 1.2 .12 .3
.5 .9 1.12 .01 .45
0.0 0.0 1. 0.0 .25
7 1100. 0.05  .1 .008  100  1.486 32.2
0.0 1100. 2200. 3300. 4400. 5500. 6600.
7*10.
7*100.
7*.75
7*5.7
2200. 4400. 6600.
```

OUTPUT

```
A SOIL MOISTURE MODEL
*********************
-------------------------------------------------------------
I    TIME        SOILV      INFIL      RAIN       FLOW I
-------------------------------------------------------------
I    20.00       2.400      0.500      0.500      0.000 I
I    40.00       1.900      0.500      0.500      0.000 I
I    60.00       1.400      0.500      0.500      0.000 I
I    80.00       0.900      0.750      0.750      0.000 I
I   100.00       0.150      0.163      0.750      0.587 I
I   120.00       0.000      0.140      0.750      0.610 I
I   140.00       0.000      0.140      1.000      0.860 I
I   160.00       0.000      0.140      1.000      0.860 I
I   180.00       0.000      0.140      1.000      0.860 I
I   200.00       0.000      0.140      0.750      0.610 I
I   220.00       0.000      0.140      0.750      0.610 I
I   240.00       0.000      0.140      0.750      0.610 I
I   260.00       0.000      0.140      0.500      0.360 I
I   280.00       0.000      0.140      0.500      0.360 I
I   300.00       0.000      0.140      0.500      0.360 I
I   320.00       0.000      0.140      0.250      0.110 I
I   340.00       0.000      0.140      0.250      0.110 I
I   360.00       0.000      0.140      0.250      0.110 I
-------------------------------------------------------------
I    20.00       3.000      0.500      0.500      0.000 I
I    40.00       2.500      0.500      0.500      0.000 I
I    60.00       2.000      0.500      0.500      0.000 I
I    80.00       1.500      0.750      0.750      0.000 I
I   100.00       0.750      0.750      0.750      0.000 I
I   120.00       0.000      0.350      0.750      0.400 I
I   140.00       0.000      0.350      1.000      0.650 I
I   160.00       0.000      0.350      1.000      0.650 I
I   180.00       0.000      0.350      1.000      0.650 I
I   200.00       0.000      0.350      0.750      0.400 I
I   220.00       0.000      0.350      0.750      0.400 I
I   240.00       0.000      0.350      0.750      0.400 I
I   260.00       0.000      0.350      0.500      0.150 I
I   280.00       0.000      0.350      0.500      0.150 I
I   300.00       0.000      0.350      0.500      0.150 I
I   320.00       0.000      0.250      0.250      0.000 I
I   340.00       0.000      0.250      0.250      0.000 I
I   360.00       0.000      0.250      0.250      0.000 I
-------------------------------------------------------------
DEPTH OF RAINFALL EXESS FOR EVERY DT min IN (ft) :
0.000 0.000 0.000 0.000 0.012 0.015 0.022 0.022 0.022 0.015 0.015 0.015 0.009 0.009 0.009 0.002 0.002 0.002
 THE PLOT NO.     1


-------------------------------------------------------------------------------------------------
I TIME             SITE 1                  SITE 2            QLATERAL   DQ/DX       YEND       I
I              Yexess      Q1          Yflow      Q2                                of DT      I
I (min)        (ft)    (cuft/DT/ft)  (ft)    (cuft/DT/ft)    (ft)       (ft)       (ft)        I
I-----------------------------------------------------------------------------------------------I
I  SECTION NO.            1                                                                    I
I    20.00     0.0000     0.0000     0.0000     0.0000       0.0000     0.000000   0.0000      I
I    40.00     0.0000     0.0000     0.0000     0.0000       0.0000     0.000000   0.0000      I
I    60.00     0.0000     0.0000     0.0000     0.0000       0.0000     0.000000   0.0000      I
I    80.00     0.0000     0.0000     0.0000     0.0000       0.0000     0.000000   0.0000      I
I   100.00     0.0122     0.1890     0.0122     0.1890       0.0122     0.000000   0.0122      I
I   120.00     0.0155     0.4687     0.0277     0.9274       0.0155     0.002293   0.0254      I
I   140.00     0.0224     0.7984     0.0479     2.5728       0.0224     0.008872   0.0390      I
I   160.00     0.0224     1.0374     0.0614     4.6142       0.0224     0.017884   0.0435      I
I   180.00     0.0224     1.0374     0.0660     5.9109       0.0224     0.024368   [illegible] I
I   200.00     0.0155     0.7984     0.0571     5.5917       0.0155     0.023966   0.0331      I
I   220.00     0.0155     0.5595     0.0486     4.3427       0.0155     0.018916   0.0297      I
```

```
I     240.00    0.0155     0.3595     0.0452     3.5491     0.0155  0.014943     0.0302 I
I     260.00    0.0085     0.3835     0.0388     2.9575     0.0085  0.012870     0.0259 I
I     280.00    0.0085     0.2076     0.0344     2.3517     0.0085  0.010721     0.0237 I
I     300.00    0.0085     0.2076     0.0323     2.0111     0.0085  0.009018     0.0233 I
I     320.00    0.0023     0.1154     0.0255     1.5919     0.0023  0.007398     0.0181 I
I     340.00    0.0023     0.0232     0.0204     1.0882     0.0023  0.005325     0.0151 I
I     360.00    0.0023     0.0232     0.0174     0.7839     0.0023  0.003804     0.0136 I
I     380.00    0.0000     0.0116     0.0136     0.5650     0.0000  0.002767     0.0108 I
I     400.00    0.0000     0.0000     0.0108     0.3791     0.0000  0.001897     0.0089 I
I     420.00    0.0000     0.0000     0.0089     0.2660     0.0000  0.001330     0.0076 I
I     440.00    0.0000     0.0000     0.0076     0.1973     0.0000  0.000987     0.0066 I
I     460.00    0.0000     0.0000     0.0066     0.1533     0.0000  0.000767     0.0059 I
I     480.00    0.0000     0.0000     0.0059     0.1231     0.0000  0.000615     0.0052 I
I     500.00    0.0000     0.0000     0.0052     0.1011     0.0000  0.000506     0.0047 I
------------------------------------------------------------------------------------------
I  SECTION NO.             2                                                             I
I      20.00    0.0000     0.0000     0.0000     0.0000     0.0000  0.000000     0.0000 I
I      40.00    0.0000     0.0000     0.0000     0.0000     0.0000  0.000000     0.0000 I
I      60.00    0.0000     0.0000     0.0000     0.0000     0.0000  0.000000     0.0000 I
I      80.00    0.0000     0.0000     0.0000     0.0000     0.0000  0.000000     0.0000 I
I     100.00    0.0122     0.1890     0.0122     0.1890     0.0122  0.000000     0.0122 I
I     120.00    0.0254     0.8285     0.0277     0.9274     0.0155  0.000495     0.0272 I
I     140.00    0.0390     1.9429     0.0497     2.6891     0.0224  0.003731     0.0459 I
I     160.00    0.0435     2.8700     0.0684     5.2734     0.0224  0.012017     0.0563 I
I     180.00    0.0416     3.0186     0.0788     7.5311     0.0224  0.022563     0.0562 I
I     200.00    0.0331     2.4451     0.0717     7.8058     0.0155  0.026803     0.0449 I
I     220.00    0.0297     1.8208     0.0604     6.2992     0.0155  0.022392     0.0380 I
I     240.00    0.0302     1.6807     0.0535     4.9084     0.0155  0.016138     0.0373 I
I     260.00    0.0259     1.5125     0.0459     3.9160     0.0085  0.012018     0.0339 I
I     280.00    0.0237     1.2290     0.0424     3.2084     0.0085  0.009897     0.0325 I
I     300.00    0.0233     1.1202     0.0410     2.9190     0.0085  0.008994     0.0321 I
I     320.00    0.0181     0.9149     0.0343     2.4750     0.0023  0.007801     0.0265 I
I     340.00    0.0151     0.6328     0.0288     1.8434     0.0023  0.006053     0.0228 I
I     360.00    0.0136     0.4938     0.0251     1.4129     0.0023  0.004595     0.0205 I
I     380.00    0.0108     0.3794     0.0205     1.0702     0.0000  0.003454     0.0170 I
I     400.00    0.0089     0.2660     0.0170     0.7733     0.0000  0.002536     0.0145 I
I     420.00    0.0076     0.1973     0.0145     0.5780     0.0000  0.001903     0.0126 I
I     440.00    0.0066     0.1533     0.0126     0.4484     0.0000  0.001475     0.0111 I
I     460.00    0.0059     0.1231     0.0111     0.3588     0.0000  0.001179     0.0099 I
I     480.00    0.0052     0.1011     0.0099     0.2943     0.0000  0.000966     0.0090 I
I     500.00    0.0047     0.0847     0.0090     0.2459     0.0000  0.000806     0.0082 I
I     520.00    0.0000     0.0388     0.0082     0.2087     0.0000  0.000850     0.0073 I
I     540.00    0.0000     0.0000     0.0073     0.1762     0.0000  0.000881     0.0064 I
I     560.00    0.0000     0.0000     0.0064     0.1447     0.0000  0.000723     0.0057 I
I     580.00    0.0000     0.0000     0.0057     0.1176     0.0000  0.000588     0.0051 I
I     600.00    0.0000     0.0000     0.0051     0.0972     0.0000  0.000486     0.0046 I
------------------------------------------------------------------------------------------
I  SECTION NO.             3                                                             I
I      20.00    0.0000     0.0000     0.0000     0.0000     0.0000  0.000000     0.0000 I
I      40.00    0.0000     0.0000     0.0000     0.0000     0.0000  0.000000     0.0000 I
I      60.00    0.0000     0.0000     0.0000     0.0000     0.0000  0.000000     0.0000 I
I      80.00    0.0000     0.0000     0.0000     0.0000     0.0000  0.000000     0.0000 I
I     100.00    0.0122     0.1890     0.0122     0.1890     0.0122  0.000000     0.0122 I
I     120.00    0.0272     0.9056     0.0277     0.9274     0.0155  0.000109     0.0276 I
I     140.00    0.0459     2.4292     0.0500     2.7144     0.0224  0.001426     0.0486 I
I     160.00    0.0563     4.1201     0.0711     5.5195     0.0224  0.006997     0.0641 I
I     180.00    0.0562     4.8056     0.0865     8.4606     0.0224  0.018275     0.0682 I
I     200.00    0.0449     4.0468     0.0837     9.5727     0.0155  0.027630     0.0561 I
I     220.00    0.0380     2.8969     0.0716     8.2409     0.0155  0.026720     0.0418 I
I     240.00    0.0373     2.4607     0.0603     6.2824     0.0155  0.019108     0.0412 I
I     260.00    0.0339     2.2430     0.0498     4.65       0.0085  0.012054     0.0377 I
I     280.00    0.0325     1.9929     0.0462     3.6        0.0085  0.008478     0.0378 I
I     300.00    0.0321     1.9029     0.0463     3.4677     0.0085  0.007824     0.0385 I
I     320.00    0.0265     1.6271     0.0408     3.1400     0.0023  0.007565     0.0332 I
I     340.00    0.0228     1.2191     0.0355     2.5185     0.0023  0.006499     0.0290 I
```

```
I    360.00   0.0205    0.9780    0.0313   [illegible]   0.0023  0.005200    0.0261 I
I    380.00   0.0170    0.7733    0.0261   [illegible]   0.0000  0.003987    0.0221 I
I    400.00   0.0145    0.5780    0.0221    1.1734    0.0000  0.002977    0.0191 I
I    420.00   0.0126    0.4484    0.0191    0.9039    0.0000  0.002277    0.0168 I
I    440.00   0.0111    0.3588    0.0168    0.7197    0.0000  0.001804    0.0150 I
I    460.00   0.0099    0.2943    0.0150    0.5885    0.0000  0.001471    0.0136 I
I    480.00   0.0090    0.2459    0.0136    0.4911    0.0000  0.001226    0.0123 I
I    500.00   0.0082    0.2087    0.0123    0.4163    0.0000  0.001038    0.0113 I
I    520.00   0.0073    0.1762    0.0113    0.3575    0.0000  0.000906    0.0104 I
I    540.00   0.0064    0.1447    0.0104    0.3098    0.0000  0.000826    0.0096 I
I    560.00   0.0057    0.1176    0.0096    0.2697    0.0000  0.000761    0.0088 I
I    580.00   0.0051    0.0972    0.0088    0.2350    0.0000  0.000689    0.0081 I
I    600.00   0.0046    0.0816    0.0081    0.2049    0.0000  0.000617    0.0075 I
I    620.00   0.0000    0.0374    0.0075    0.1793    0.0000  0.000709    0.0068 I
I    640.00   0.0000    0.0000    0.0068    0.1548    0.0000  0.000774    0.0060 I
I    660.00   0.0000    0.0000    0.0060    0.1290    0.0000  0.000645    0.0054 I
I    680.00   0.0000    0.0000    0.0054    0.1061    0.0000  0.000531    0.0049 I
-----------------------------------------------------------------------------------
I  SECTION NO.          4                                                         I
I     20.00   0.0000    0.0000    0.0000    0.0000    0.0000  0.000000    0.0000 I
I     40.00   0.0000    0.0000    0.0000    0.0000    0.0000  0.000000    0.0000 I
I     60.00   0.0000    0.0000    0.0000    0.0000    0.0000  0.000000    0.0000 I
I     80.00   0.0000    0.0000    0.0000    0.0000    0.0000  0.000000    0.0000 I
I    100.00   0.0122    0.1890    0.0122    0.1890    0.0122  0.000000    0.0122 I
I    120.00   0.0276    0.9226    0.0277    0.9274    0.0155  0.000024    0.0277 I
I    140.00   0.0486    2.6166    0.0501    2.7200    0.0224  0.000517    0.0496 I
I    160.00   0.0641    4.8643    0.0720    5.6081    0.0224  0.003719    0.0683 I
I    180.00   0.0682    6.2917    0.0908    8.9550    0.0224  0.013316    0.0774 I
I    200.00   0.0561    5.6983    0.0929   10.8710    0.0155  0.025863    0.0671 I
I    220.00   0.0448    4.0327    0.0825   10.0923    0.0155  0.030298    0.0523 I
I    240.00   0.0412    3.0744    0.0677    7.8222    0.0155  0.023739    0.0440 I
I    260.00   0.0377    2.6617    0.0525    3.4151    0.0085  0.013767    0.0388 I
I    280.00   0.0378    2.4680    0.0473    3.9422    0.0085  0.007371    0.0399 I
I    300.00   0.0385    2.5108    0.0485    3.6738    0.0085  0.005815    0.0427 I
I    320.00   0.0332    2.2725    0.0450    3.5271    0.0023  0.006273    0.0387 I
I    340.00   0.0290    1.7932    0.0410    3.0690    0.0023  0.006379    0.0346 I
I    360.00   0.0261    1.4631    0.0369    2.6049    0.0023  0.005709    0.0312 I
I    380.00   0.0221    1.1734    0.0312    2.0869    0.0000  0.004567    0.0266 I
I    400.00   0.0191    0.9039    0.0266    1.5881    0.0000  0.003421    0.0232 I
I    420.00   0.0168    0.7197    0.0232    1.2384    0.0000  0.002593    0.0206 I
I    440.00   0.0150    0.5885    0.0206    0.9987    0.0000  0.002051    0.0186 I
I    460.00   0.0136    0.4911    0.0186    0.8281    0.0000  0.001685    0.0169 I
I    480.00   0.0123    0.4163    0.0169    0.7005    0.0000  0.001421    0.0154 I
I    500.00   0.0113    0.3575    0.0154    0.6010    0.0000  0.001218    0.0142 I
I    520.00   0.0104    0.3098    0.0142    0.5214    0.0000  0.001058    0.0132 I
I    540.00   0.0096    0.2697    0.0132    0.4564    0.0000  0.000934    0.0122 I
I    560.00   0.0088    0.2350    0.0122    0.4025    0.0000  0.000837    0.0114 I
I    580.00   0.0081    0.2049    0.0114    0.3568    0.0000  0.000759    0.0106 I
I    600.00   0.0075    0.1793    0.0106    0.3175    0.0000  0.000691    0.0099 I
I    620.00   0.0068    0.1548    0.0099    0.2834    0.0000  0.000643    0.0093 I
I    640.00   0.0060    0.1290    0.0093    0.2535    0.0000  0.000622    0.0087 I
I    660.00   0.0054    0.1061    0.0087    0.2263    0.0000  0.000601    0.0081 I
I    680.00   0.0049    0.0885    0.0081    0.2013    0.0000  0.000564    0.0075 I
I    700.00   0.0000    0.0404    0.0075    0.1785    0.0000  0.000690    0.0068 I
I    720.00   0.0000    0.0000    0.0068    0.1553    0.0000  0.000777    0.0061 I
I    740.00   0.0000    0.0000    0.0061    0.1299    0.0000  0.000649    0.0054 I
I    760.00   0.0000    0.0000    0.0054    0.1068    0.0000  0.000534    0.0049 I
-----------------------------------------------------------------------------------
I  SECTION NO.          5                                                         I
I     20.00   0.0000    0.0000    0.0000    0.0000    0.0000  0.000000    0.0000 I
I     40.00   0.0000    0.0000    0.0000    0.0000    0.0000  0.000000    0.0000 I
I     60.00   0.0000    0.0000    0.0000    0.0000    0.0000  0.000000    0.0000 I
I     80.00   0.0000    0.0000    0.0000    0.0000    0.0000  0.000000    0.0000 I
I    100.00   0.0122    0.1890    0.0122    0.1890    0.0122  0.000000    0.0122 I
I    120.00   0.0277    0.9264    0.0277    0.9274    0.0155  0.000005    0.0277 I
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|   140.00   0.0496   2.6850   0.0502    2.7212   0.0224  0.000181    0.0500 |
|   160.00   0.0683   5.2676   0.0724    5.6391   0.0224  0.001858    0.0705 |
|   180.00   0.0774   7.4102   0.0930    9.2033   0.0224  0.008966    0.0840 |
|   200.00   0.0671   7.3086   0.0995   11.7575   0.0155  0.022245    0.0772 |
|   220.00   0.0523   5.3414   0.0927   11.7339   0.0155  0.031962    0.0608 |
|   240.00   0.0440   3.7174   0.0763    9.5102   0.0155  0.028964    0.0473 |
|   260.00   0.0388   2.8856   0.0558    6.3582   0.0085  0.017363    0.0385 |
|   280.00   0.0399   2.6483   0.0470    4.1520   0.0085  0.007518    0.0395 |
|   300.00   0.0427   2.8718   0.0480    3.6261   0.0085  0.003772    0.0443 |
|   320.00   0.0387   2.8015   0.0466    3.5974   0.0023  0.003979    0.0426 |
|   340.00   0.0346   2.3549   0.0449    3.3991   0.0023  0.005221    0.0396 |
|   360.00   0.0312   1.9664   0.0419    3.1192   0.0023  0.005764    0.0362 |
|   380.00   0.0266   1.5881   0.0362    2.6225   0.0000  0.005172    0.0310 |
|   400.00   0.0232   1.2384   0.0310    2.0402   0.0000  0.004009    0.0270 |
|   420.00   0.0206   0.9987   0.0270    1.5960   0.0000  0.002987    0.0240 |
|   440.00   0.0186   0.8281   0.0240    1.2873   0.0000  0.002296    0.0217 |
|   460.00   0.0169   0.7005   0.0217    1.0723   0.0000  0.001859    0.0199 |
|   480.00   0.0154   0.6010   0.0199    0.9146   0.0000  0.001568    0.0183 |
|   500.00   0.0142   0.5214   0.0183    0.7923   0.0000  0.001354    0.0169 |
|   520.00   0.0132   0.4564   0.0169    0.6937   0.0000  0.001186    0.0157 |
|   540.00   0.0122   0.4025   0.0157    0.6122   0.0000  0.001049    0.0147 |
|   560.00   0.0114   0.3568   0.0147    0.5440   0.0000  0.000936    0.0138 |
|   580.00   0.0106   0.3175   0.0138    0.4862   0.0000  0.000843    0.0129 |
|   600.00   0.0099   0.2834   0.0129    0.4365   0.0000  0.000765    0.0122 |
|   620.00   0.0093   0.2535   0.0122    0.3935   0.0000  0.000700    0.0115 |
|   640.00   0.0087   0.2263   0.0115    0.3559   0.0000  0.000648    0.0108 |
|   660.00   0.0081   0.2013   0.0108    0.3227   0.0000  0.000607    0.0102 |
|   680.00   0.0075   0.1785   0.0102    0.2929   0.0000  0.000572    0.0096 |
|   700.00   0.0068   0.1553   0.0096    0.2660   0.0000  0.000554    0.0091 |
|   720.00   0.0061   0.1299   0.0091    0.2413   0.0000  0.000557    0.0085 |
|   740.00   0.0054   0.1068   0.0085    0.2179   0.0000  0.000556    0.0080 |
|   760.00   0.0049   0.0890   0.0080    0.1954   0.0000  0.000532    0.0074 |
|   780.00   0.0000   0.0407   0.0074    0.1744   0.0000  0.000669    0.0068 |
|   800.00   0.0000   0.0000   0.0068    0.1524   0.0000  0.000762    0.0060 |
|   820.00   0.0000   0.0000   0.0060    0.1277   0.0000  0.000639    0.0054 |
|   840.00   0.0000   0.0000   0.0054    0.1052   0.0000  0.000526    0.0048 |
------------------------------------------------------------------------------
```